



GEOLOGICAL SURVEY OF CANADA
BULLETIN 571

**SEDIMENTOLOGY, SEQUENCE STRATIGRAPHY,
ORGANIC PETROLOGY, GEOCHEMISTRY, AND
PALYNOLOGY OF MANNVILLE GROUP
COALS IN SOUTH-CENTRAL ALBERTA**

I. Banerjee and W. Kalkreuth



2002

GEOLOGICAL SURVEY OF CANADA
BULLETIN 571

**SEDIMENTOLOGY, SEQUENCE STRATIGRAPHY,
ORGANIC PETROLOGY, GEOCHEMISTRY, AND
PALYNOLOGY OF MANNVILLE GROUP
COALS IN SOUTH-CENTRAL ALBERTA**

I. Banerjee and W. Kalkreuth

2002

©Her Majesty the Queen in Right of Canada, 2002
Catalogue No. M42-571E
ISBN 0-660-18538-5

Available in Canada from
Geological Survey of Canada offices:

601 Booth Street
Ottawa, Ontario K1A 0E8

3303-33rd Street N.W.
Calgary, Alberta T2L 2A7

101-605 Robson Street
Vancouver, B.C. V6B 5J3

A deposit copy of this publication is available for
reference in public libraries across Canada

Price subject to change without notice

Critical readers

J. Dixon
L. Stasiuk
J. White

Authors' addresses

Indranil Banerjee (retired)
7324 61 Avenue NW
Calgary, AB T3B 3W8

Wolfgang Kalkreuth
Instituto de Geosciências
Universidade Federal do Rio Grande do Sul
Av. Bento Gonçalves
9500, 91501-970 Porto Alegre, RS
Brazil

Manuscript submitted: 00-10
Approved for publication: 02-05

CONTENTS

1	Abstract
1	Résumé
1	Summary
2	Sommaire
3	Introduction
4	Study area
4	Methods and objectives
6	Acknowledgments
6	Cretaceous coals of the Western Interior Seaway
7	Regional stratigraphy
7	Paleogeography
8	Lithostratigraphy and lithofacies of the coal-bearing strata
8	Lower Mannville subgroup
9	The Detrital zone (Deville Formation)
9	Ellerslie Formation
11	The Ostracode zone
11	The Middle Mannville subgroup
11	The Glauconitic Sandstone
12	The Upper Mannville subgroup
13	Paleoenvironmental evolution and the coal-forming environment
19	The paralic nature of the Mannville coals
20	The Mannville Group as a sequence
21	Sequence stratigraphy
21	Introduction
21	Third-order sequences
23	Sequence stratigraphy of coal seams
23	Previous work
23	Sequence stratigraphy of Mannville coals
25	Pattern of coal seam splits: the fourth-order sequences
26	Coal seam splits and TR cycles
27	Geochemical and petrological signatures of coal seams
27	Analytical procedures
27	Petrographic analysis
27	Sulphur determination
27	Rock-Eval
27	Typical signatures of coal seams
28	Summary of palynology of coal seams
28	The Twin Coal depositional model
30	Detailed study of the Medicine River and the G seams
30	Coal seam stratigraphy
31	Study of coal seam split (location Y)
33	Petrography of the LMR seam, lower leaf
33	Geochemistry of the LMR seam, lower leaf
33	Palynology of the LMR seam, lower leaf
34	Petrography of the LMR seam, upper leaf
35	Palynology of the LMR seam, upper leaf
35	The G seam
37	Petrography of the G seam
42	Geochemistry of the G seam
42	Palynology of the G seam
42	Coal seam profile of the amalgamated Medicine River seam
43	Cycles within the amalgamated Medicine River seam
44	Petrography of the amalgamated Medicine River seam
44	Full seam characteristics

44	In-seam variations and TR cycles
45	Lower leaf
48	Upper leaf
48	Distribution of sulphur content
49	Coal seam sequence stratigraphy
50	Conclusions
50	References

Appendix

54	List of cores studied
----	-----------------------

Figures

3	1. Lithostratigraphy, age and map and geological cross-section showing location of study area
4	2. Stratigraphic correlation chart of the Mannville Group and its coal zones in outcrop and in the subsurface
5	3. Summary stratigraphic cross-sections along three regional lines
6	4. Sequence stratigraphy of the Mannville Group interpreted as a second-order depositional sequence
7	5. Regional isopach map of the Mannville Group
8	6. Enlarged view of study area showing strike and dip sections
9	7. Core photograph showing sub-Mannville unconformity
10	8. A combined lithostratigraphic and sequence stratigraphic subdivision of the Mannville subgroup
12	9. Sequence stratigraphic framework of the Mannville Group based on subsurface correlation of geophysical logs
17	10. SP and lithological logs of the cored interval of the Lower Mannville Group
18	11. Wave- and tide-generated structures in the studied sequences
19	12. Core photograph of the third-order sequence boundary at the top of the Ostracode zone
20	13. Lithology log of the cored interval in well 10-25-40-25W4
22	14. Detailed core photographs of coal-bearing strata in well 6-6-38-19W4
24	15. Lithology log of incised-valley-fill deposits
25	16. Core photographs of trace fossils in coal-bearing and adjacent strata
26	17. A sequence stratigraphic interpretation of the cross-section of lines 1, 2 and 3 in Figure 3, showing the hierarchy of sequences within the Mannville Group
27	18. A coal seam split produced in a single transgressive-regressive (TR) cycle as envisaged in a model by Diessel (1992)
28	19. Ideal signatures in coal character profiles for transgressive and regressive seams
29	20. Succession of palynoflora in a typical Lower Cretaceous Mannville Group transgressive seam indicating decreasing influence of tree cover and increasing influence of salinity toward the roof of the seam
30	21. A conceptual model illustrating the relationship between TR coal couplets, merging of the higher order sequence boundaries into lower order ones, and formation of an amalgamated coal seam on a progradational platform over a series of stacked progradational wedges of higher order sequences
31	22. The origin of fourth-order sequences through base level cycles
32	23. Stacking pattern of parasequences in a third-order sequence contained within a coal-seam split
32	24. Diagrammatic interpretation of patterns of coal seam splits and mergers and their relationship with sequence boundaries
34	25. Stratigraphic cross-section based on gamma-ray density log showing detailed study of coal seam splits in the LMR coal seam
38	26. Coal character profiles of the lower leaf of the LMR coal seam
39	27. Petrographic profile of the upper leaf of the LMR coal seam
40	28. Core photographs illustrating the detailed stratigraphic relationship between the G seam and adjacent sedimentary strata
42	29. Coal character profiles of the G seam in well 10-25-40-25W4
44	30. Core and geophysical (gamma-ray) logs of well 07-01-37-21W4, showing locations of three orders of sequence boundaries
45	31. Petrographic characteristics, sulphur content, sequence boundaries and TR cycles for the amalgamated Medicine River seam: in well 07-01-37-21W4
46	32. Petrographic and palynological characteristics of the amalgamated Medicine River seam in relation to sequence boundaries, TR cycles and prevailing mire types during peat accumulation

- 49 33. Core photograph of the 2.9 m thick strata underlying the amalgamated Medicine River seam in well
07-01-37-21W4

Tables

- 29 1. Significant characteristics of the palynocommunities of the Mannville Group coal seams
36 2. Petrographic characteristics, LMR seam, lower leaf
38 3. Petrographic characteristics, LMR seam, upper leaf
41 4. Petrographic characteristics, G seam
48 5. Average petrographic characteristics for the amalgamated Medicine River seam in well 07-01-37-21W4
based on automated image analyses

SEDIMENTOLOGY, SEQUENCE STRATIGRAPHY, ORGANIC PETROLOGY, GEOCHEMISTRY, AND PALYNOLOGY OF MANNVILLE GROUP COALS IN SOUTH-CENTRAL ALBERTA

Abstract

An integrated case study of the stratigraphy, sedimentology, geochemistry, organic petrology and palynology of subsurface coal and coal-bearing strata of the Lower Cretaceous Mannville Group has resulted in the construction of a sequence stratigraphic model of paralic coal. In Alberta, the unconformity-bounded Mannville Group is a 100 to 300 m thick, siliciclastic unit comprising a second-order depositional sequence that can be divided into six third-order sequences. The databases for this study consisted of geophysical logs, examination of cored intervals, and organic petrological and geochemical analyses of samples of coal and associated rocks.

Examination of the stratigraphy, sedimentology, and palynological, petrographic, and geochemical profiles of three specific coal seams also revealed high-frequency fourth-order sequences and, in a 12 m thick coal seam, at least three transgressive-regressive cycles and two unconformities.

Résumé

Une étude de cas intégrée de la stratigraphie, de la sédimentologie, de la géochimie, de la pétrologie organique et de la palynologie du charbon de subsurface et des strates houillères du Groupe de Mannville du Crétacé inférieur, a mené à l'élaboration d'un modèle stratigraphique séquentiel du charbon paralic. En Alberta, le Groupe de Mannville, qui est limité par des discordances, est une unité silicoclastique de 100 à 300 m d'épaisseur; il comprend une séquence de deuxième ordre qui peut être divisée en six séquences de troisième ordre. Les bases de données de l'étude ont été constituées d'après des diagaphies géophysiques, par l'examen d'intervalles carottés et d'après des analyses pétrologiques organiques et géochimiques d'échantillons de charbon et de roches associées.

L'examen de la stratigraphie, de la sédimentologie et des profils palynologiques, pétrographiques et géochimiques de trois filons de charbon particuliers a aussi révélé la présence de séquences de quatrième ordre à fréquence élevée et, dans un filon houiller de 12 m d'épaisseur, d'au moins trois cycles de transgression-régression et deux discordances.

Summary

An integrated case study of the stratigraphy, sedimentology, geochemistry, organic petrology, and palynology of coal and coal-bearing strata of the Lower Cretaceous Mannville Group, south-central Alberta, Canada, led to the construction of a sequence stratigraphic model of paralic coal. The database for this study consisted of geophysical logs, examination of cored intervals, and analyses of samples of coal and associated rocks.

The unconformity-bounded Mannville Group in Alberta is a 100 to 300 m thick, siliciclastic, second-order depositional sequence that can be divided into six third-order sequences. Coal seams are confined to highstand systems tracts and the thickest and most extensive one (the Medicine River seam) lies close to the maximum flooding surface of the second-order sequence. Most coal seams overlie third-order sequence boundaries, which generally coincide with transgressive surfaces.

Coals were analyzed for the following parameters to determine whether they were deposited in a transgressive or regressive environment: sulphur content (S), hydrogen index (HI), tissue preservation index (TPI), gellification index (GI), and vitrinite/interinite ratio (V/I). In transgressive seams, S and HI tend to increase upward close to the marine roof rock as a result of the enrichment in lipid-rich degraded components and the availability of sulphate in marine water. The degree of bacterial activity in the precursor mire decreases upward, resulting in an upward decrease of both TPI and V/I. Regressive seams are characterized by a general upward decrease in vitrinite content and a predominance of detrital maceral content (inertodetrinite and vitrodetrinite). TPI is typically low throughout regressive seams except at the very base. GI decreases and vitrinite reflectance increases toward the top.

The typical palynological profile of a transgressive coal seam in the Mannville Group shows the following succession of seven recognizable palynofacies (from bottom to top): 1. *Taxodium/Cedrus* forest bog; 2. *Taxodium* swamp; 3. *Taxodium/Gleichenia* fen; 4. *Gleichenia* dry marsh; 5. *Zygnemia/Gleichenia* freshwater marsh; 6. *Polypodium* brackish marsh; and 7. marine shales with dinoflagellates. The reverse succession signifies a regressive seam.

Examination of the stratigraphy, sedimentology, and palynological, petrographic, and geochemical profiles of the split Lower Medicine River (LMR) seam and the G seam ("Glaucconitic coal zone" of previous authors such as Strobl, 1988) revealed that these splits delineate high-frequency (fourth-order) sequences. These were produced in single transgressive-regressive cycles stacked in a series of progradational wedges within subhorizontal third-order sequence boundaries (Banerjee et al., 1996). Study of a 12 m core of an amalgamated Upper Medicine River (UMR) seam revealed a complex petrological, geochemical, and palynological profile with at least three transgressive-regressive cycles and two unconformities (third-order sequence boundaries) within the seam.

Sommaire

Une étude de cas intégrée de la stratigraphie, de la sédimentologie, de la géochimie, de la pétrologie organique et de la palynologie du charbon et des strates houillères du Groupe de Mannville du Crétacé inférieur, dans le centre sud de l'Alberta, au Canada, a mené à l'élaboration d'un modèle stratigraphique séquentiel du charbon paralytique. La base de données de cette étude a été constituée d'après des diagraphies géophysiques, par l'examen d'intervalles carottés et d'après l'analyse d'échantillons de charbon et de roches associées.

En Alberta, le Groupe de Mannville, qui est limité par des discordances, est une séquence silicoclastique de deuxième ordre, dont l'épaisseur varie de 100 à 300 m, qui peut être divisée en six séquences de troisième ordre. Les filons de charbon se rencontrent dans des cortèges de haut niveau et le plus épais et le plus étendu (le filon de Medicine River) repose près de la surface d'inondation maximale de la séquence de deuxième ordre. La plupart des filons de charbon reposent sur les limites des séquences de troisième ordre, lesquelles coïncident généralement avec des surfaces de transgression.

Pour déterminer si les charbons ont été déposés dans un milieu de transgression ou de régression, on les a analysés d'après les paramètres suivants : teneur en soufre, indice d'hydrogène, indice de préservation du tissu, indice de gélification et rapport vitrinite/intérinite. Dans les filons transgressifs, la teneur en soufre et l'indice d'hydrogène augmentent vers le haut près de la roche couverture marine en raison de l'enrichissement en composants dégradés riches en lipides et de la disponibilité des sulfates dans l'eau de mer. Le niveau d'activité bactérienne dans le bournier précurseur diminue vers le haut, donnant lieu à une diminution vers le haut à la fois de l'indice de préservation du tissu et du rapport vitrinite/intérinite. Les filons régressifs sont caractérisés par une diminution générale vers le haut de la teneur en vitrinite et par la prédominance de la teneur en macéraux détritiques (inertodétrinite et vitrodétrinite). L'indice de préservation du tissu est généralement faible dans l'ensemble des filons régressifs, sauf à la base. Vers le sommet, l'indice de gélification diminue, alors que la réflectance de la vitrinite augmente.

Le profil palynologique caractéristique d'un filon de charbon transgressif du Groupe de Mannville présente la succession suivante de sept palynofaciès identifiables (de bas en haut) : 1. tourbière oligotrophe boisée à *Taxodium/Cedrus*, 2. marécage à *Taxodium*, 3. tourbière minérotrophe à *Taxodium/Gleichenia*, 4. marais asséché à *Gleichenia*, 5. marais d'eau douce à *Zygnemia/Gleichenia*, 6. marais saumâtre à *Polypodium*; et 7. shale marin à dinoflagellés. Une succession inverse indique un filon régressif.

L'examen de la stratigraphie, de la sédimentologie et des profils palynologiques, pétrographiques et géochimiques du filon divisé de Medicine River inférieur et du filon G («zone de charbon glauconieux» d'après de précédents auteurs, tel Strobl, 1988) a démontré que ces divisions délimitent des séquences à fréquence élevée (quatrième ordre). Celles-ci se sont constituées au cours de cycles de transgression-régression et empilées en séries de biseaux de progradation à l'intérieur des limites de séquences de troisième ordre (Banerjee et al., 1996). L'étude d'une carotte de 12 m extraite d'un filon amalgamé de Medicine River supérieure a démontré un profil pétrologique, géochimique et palynologique complexe avec au moins trois cycles de transgression-régression et deux discordances (limites de séquences de troisième ordre) à l'intérieur du filon.

INTRODUCTION

With the introduction of sequence stratigraphic concepts in coal geology (Cross, 1988; Diessel, 1992), the relationship between transgressive-regressive (TR) cycles and the stratigraphic architecture of coal seams has become the focus for renewed research on the factors controlling coal formation. In a series of recent studies, the concept of classical coal cyclothems has been reinterpreted in terms of sequence stratigraphy (Gibling and Bird, 1994; Arditto, 1991) and coal-bearing successions have been analyzed in terms of both sequence stratigraphic (Posamentier and Vail, 1988) and genetic stratigraphic (Galloway, 1989) models in several interesting examples (Arditto, 1991; Flint et al., 1995; Gastaldo et al., 1993; Hamilton and Tadros, 1994; Hampson, 1995; Read, 1995).

In the present study, the sequence stratigraphic analysis of some paralic coal seams in the Lower Cretaceous Mannville Group (Fig. 1–4) of the Western Canada Sedimentary Basin (WCSB) is presented within a hierarchical framework of three orders of depositional sequences (second to fourth). This analysis is based on an integrated database of lithostratigraphy, sedimentology, palynology, organic petrology, and geochemistry. A unique aspect of this study is an emphasis on the following three key stratigraphic features of coal seams in analyzing their sequence stratigraphic relations:

1. Patterns of coal-seam splits and their relation to transgressive-regressive cycles.

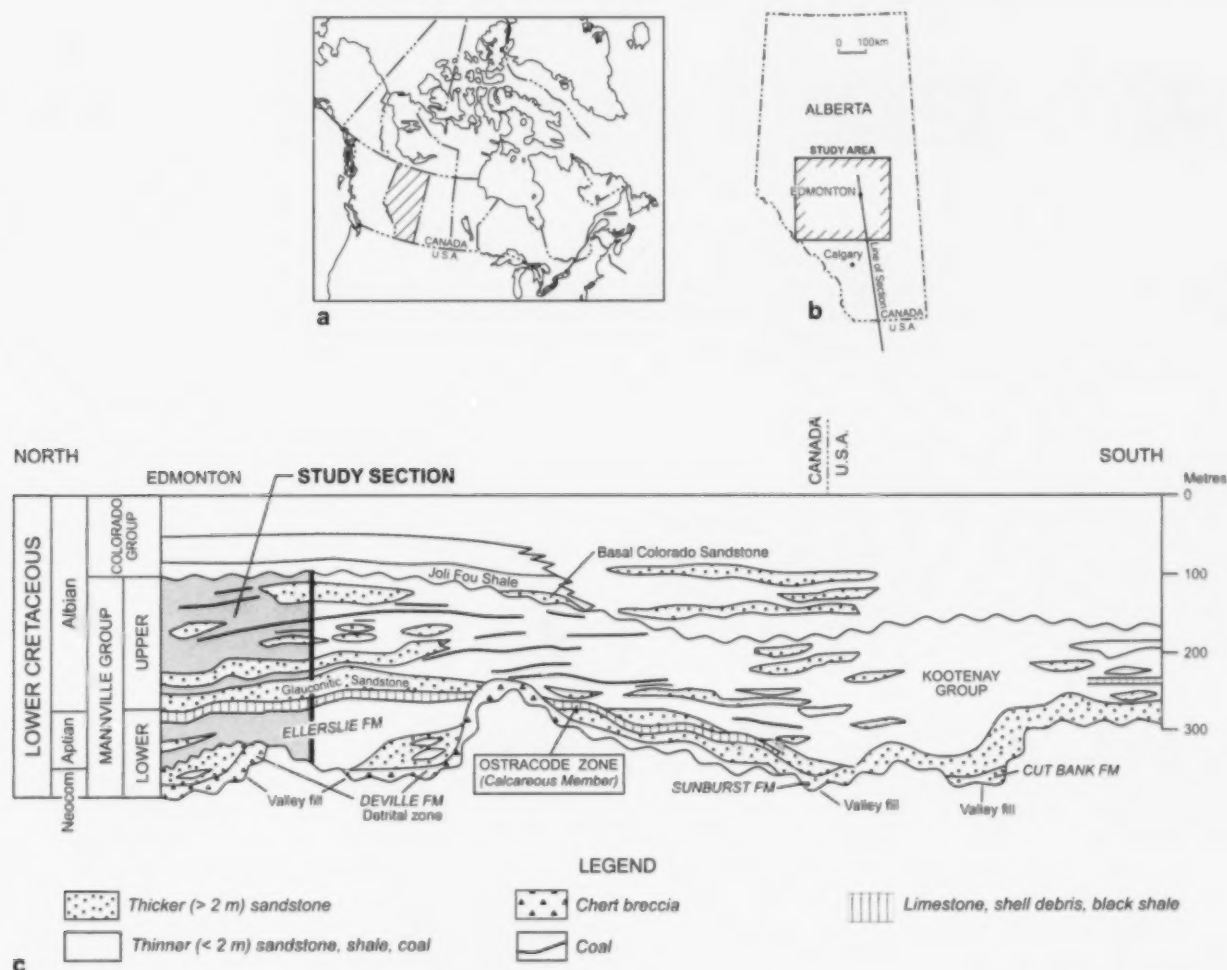


Figure 1. Lithostratigraphy, age, and map and geological cross-section showing location of study area. **a.** Location of Alberta in North America; **b.** location of the study area within Alberta and of the line of cross-section shown in **c**; **c.** generalized lithostratigraphic cross-section of the Mannville Group showing parts of the stratigraphic section studied (shaded area).

Lower Cretaceous	Northeastern Plains			Central Foothills		Central Plains	
	Alban			LUSLAR GROUP		MANNVILLE GROUP	
	MANNVILLE GROUP						
	Alban						
			GRAND RAPIDS FORMATION		GATES FM		
			CLEARWATER FORMATION		Coal zone		Coal zone
			M-MURRAY FORMATION		MOOSEBAR FM		Upper Mannville subg.
			Firebag Coal zone		GLADSTONE FORMATION		Glaucous Ss
							Oil shale zone
							ELLERSLIE FM
					CADOMIN FM		

Figure 2. Stratigraphic correlation chart of the Mannville Group and its coal zones in outcrop and in the subsurface (after Langenberg et al., 1997).

2. Characterizing the transgressive or regressive natures of coal seams using typical signatures in vertical changes in petrological, geochemical, and palynological parameters.
3. Recognizing multiple TR cycles and subtle unconformities within a thick (>12 m), regionally extensive coal seam.

In a simple model, Diessel (1992) interpreted a coal-seam split produced by a single TR cycle as the basic building block of sequence stratigraphy of paralic coals. The transgressive-regressive nature of the coal seam couplet can be corroborated by the typical profiles of coal parameters (petrological, geochemical and palynological) which are distinctive for both transgressive and regressive seams (Diessel, 1992). In thick coal seams (>5 m), which in all probability are the result of amalgamation of several high-frequency sequences, profiles of coal characteristics would be complex and unconformities would occur within seams. Criteria to recognize such unconformities based on organic petrological and geochemical characters are available (Shearer et al., 1994).

In the following case study of the coal seams of the Mannville Group of Alberta, all three key stratigraphic features mentioned above have been used to analyze the hierarchical orders of sequences that have been superposed on one another to produce the regionally extensive, thick (12 m), Medicine River coal seam, which splits repeatedly basinward (see splits marked 1 and 2 in Fig. 3b).

Study area

The study area is situated in south-central Alberta, between latitude 51°40'–52°40'N and longitude 112°20'–113°30'W

(Fig. 1). It covers an area of approximately 9000 km², and is centred around the town of Red Deer between Townships 24 and 58 and Ranges 6W4 to R15W5 (Fig. 5, 6). Although the subsurface stratigraphy of the coal and coal-bearing strata was studied throughout this area, detailed analytical study of coal seams was confined to six wells within a much smaller area (Twp. 37–40, Rge. 21–25W4). Detailed laboratory studies were carried out on cored intervals of coal.

In the context of regional Mannville paleogeography, the area is located in a back-barrier environment landward of two prominent barriers (Chiang, 1984; Leckie and Smith, 1992) mapped in the subsurface. The Mannville isopach in the area (Fig. 5) illustrates the basinward (northwesterly) thickening of the strata and a local thinning over a paleotopographic high at the southeastern end of the study area.

Methods and objectives

This study is based entirely on data retrieved from subsurface strata. The database consists of approximately 547 geophysical well-logs (mostly gamma-ray and density-neutron), 25 subsurface cross-sections constructed from the logs, and a number of isopach and structure contour maps of the area.

Cored intervals with a cumulative length of 1500 m gathered from 114 wells were logged for examination of key surfaces, sedimentary structures, and trace fossils. Approximately 100 samples of coal and associated rocks were collected from six wells for palynological analysis (Fig. 6). Organic petrological and geochemical analyses were also done in a total of 20 m of columnar samples collected from three coal seams in three well locations (Fig. 6). These columnar samples were used for descriptions of lithotypes, determination of petrographic composition (macerals), vitrinite reflectance measurement, and geochemistry (Rock-Eval pyrolysis, sulphur).

The analyses were used to construct vertical profiles of coal parameters. Palynological analyses of coals provided further data from which paleocommunities of floras and floral successions were reconstructed.

The objectives of the study were to: 1) construct a regional stratigraphic framework of the Mannville Group based on three strike-parallel and seven dip-parallel subsurface cross-sections; 2) correlate the regional coal seams and produce a detailed stratigraphic analysis of coal seam splits, pinchouts and washouts; 3) conduct a facies analysis of the coal-bearing strata in terms of lithological succession, sedimentary structures, trace fossils, and palynology from examination of cored intervals; 4) produce

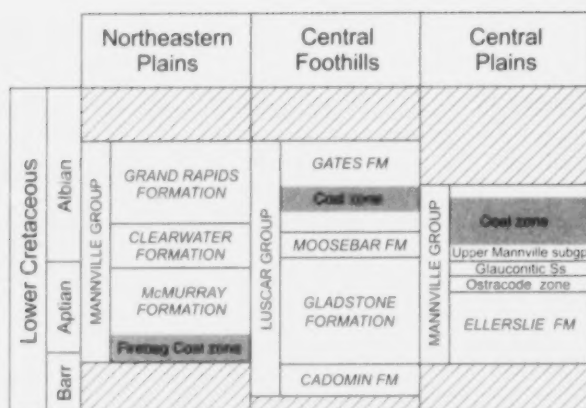


Figure 2. Stratigraphic correlation chart of the Mannville Group and its coal zones in outcrop and in the subsurface (after Langenberg et al., 1997).

2. Characterizing the transgressive or regressive natures of coal seams using typical signatures in vertical changes in petrological, geochemical, and palynological parameters.
3. Recognizing multiple TR cycles and subtle unconformities within a thick (>12 m), regionally extensive coal seam.

In a simple model, Diessel (1992) interpreted a coal-seam split produced by a single TR cycle as the basic building block of sequence stratigraphy of paralic coals. The transgressive-regressive nature of the coal seam couplet can be corroborated by the typical profiles of coal parameters (petrological, geochemical and palynological) which are distinctive for both transgressive and regressive seams (Diessel, 1992). In thick coal seams (>5 m), which in all probability are the result of amalgamation of several high-frequency sequences, profiles of coal characteristics would be complex and unconformities would occur within seams. Criteria to recognize such unconformities based on organic petrological and geochemical characters are available (Shearer et al., 1994).

In the following case study of the coal seams of the Mannville Group of Alberta, all three key stratigraphic features mentioned above have been used to analyze the hierarchical orders of sequences that have been superposed on one another to produce the regionally extensive, thick (12 m), Medicine River coal seam, which splits repeatedly basinward (see splits marked 1 and 2 in Fig. 3b).

Study area

The study area is situated in south-central Alberta, between latitude 51°40'–52°40'N and longitude 112°20'–113°30'W

(Fig. 1). It covers an area of approximately 9000 km², and is centred around the town of Red Deer between Townships 24 and 58 and Ranges 6W4 to R15W5 (Fig. 5, 6). Although the subsurface stratigraphy of the coal and coal-bearing strata was studied throughout this area, detailed analytical study of coal seams was confined to six wells within a much smaller area (Twp. 37–40, Rge. 21–25W4). Detailed laboratory studies were carried out on cored intervals of coal.

In the context of regional Mannville paleogeography, the area is located in a back-barrier environment landward of two prominent barriers (Chiang, 1984; Leckie and Smith, 1992) mapped in the subsurface. The Mannville isopach in the area (Fig. 5) illustrates the basinward (northwesterly) thickening of the strata and a local thinning over a paleotopographic high at the southeastern end of the study area.

Methods and objectives

This study is based entirely on data retrieved from subsurface strata. The database consists of approximately 547 geophysical well-logs (mostly gamma-ray and density-neutron), 25 subsurface cross-sections constructed from the logs, and a number of isopach and structure contour maps of the area.

Cored intervals with a cumulative length of 1500 m gathered from 114 wells were logged for examination of key surfaces, sedimentary structures, and trace fossils. Approximately 100 samples of coal and associated rocks were collected from six wells for palynological analysis (Fig. 6). Organic petrological and geochemical analyses were also done in a total of 20 m of columnar samples collected from three coals seams in three well locations (Fig. 6). These columnar samples were used for descriptions of lithotypes, determination of petrographic composition (macerals), vitrinite reflectance measurement, and geochemistry (Rock-Eval pyrolysis, sulphur).

The analyses were used to construct vertical profiles of coal parameters. Palynological analyses of coals provided further data from which paleocommunities of floras and floral successions were reconstructed.

The objectives of the study were to: 1) construct a regional stratigraphic framework of the Mannville Group based on three strike-parallel and seven dip-parallel subsurface cross-sections; 2) correlate the regional coal seams and produce a detailed stratigraphic analysis of coal seam splits, pinchouts and washouts; 3) conduct a facies analysis of the coal-bearing strata in terms of lithological succession, sedimentary structures, trace fossils, and palynology from examination of cored intervals; 4) produce

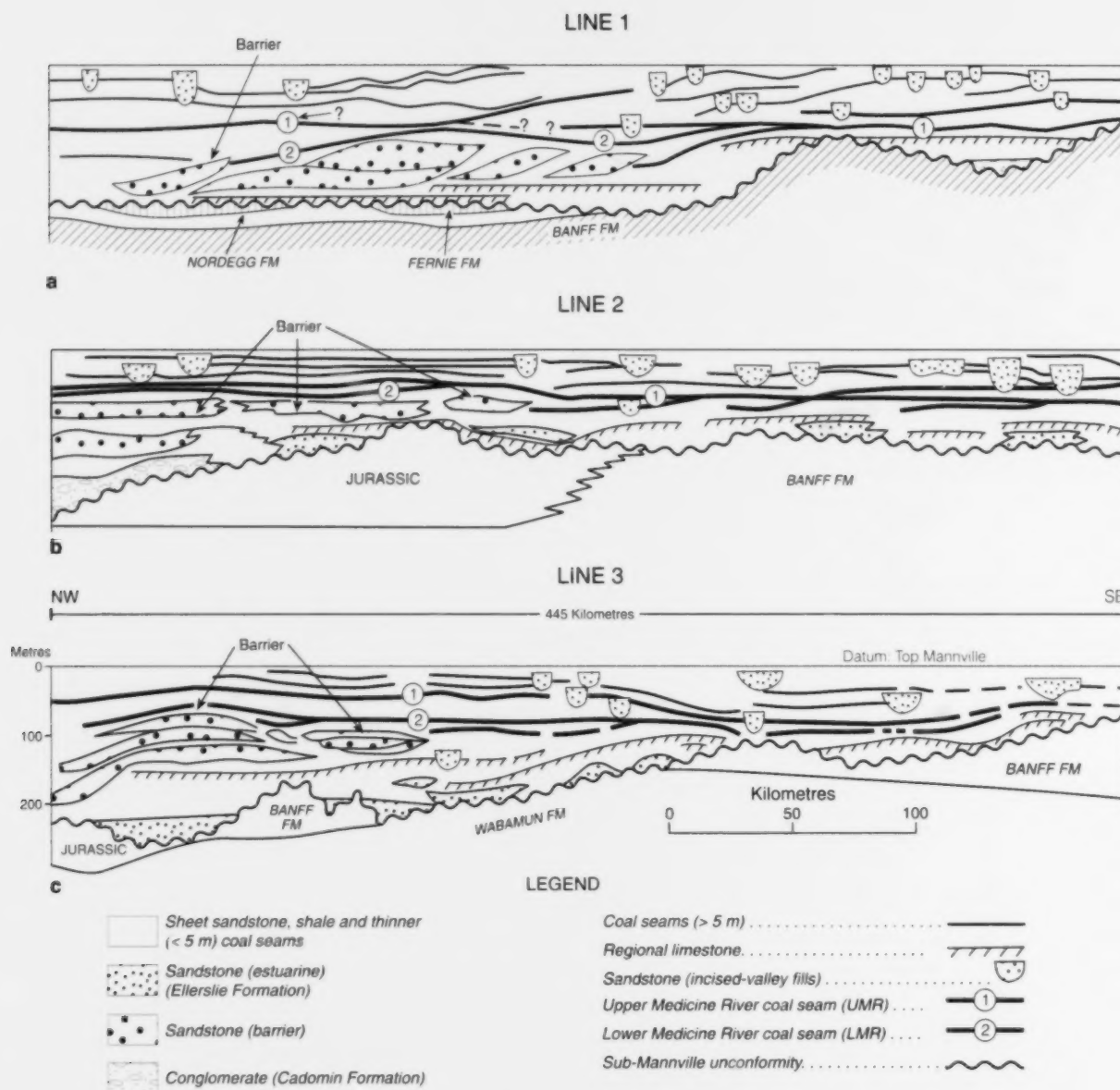


Figure 3. Summary stratigraphic cross-sections (strike sections) along three regional lines (see Fig. 6 for location) based on 120 to 150 geophysical logs. Only thick (>30 m) sandstone bodies, key horizons of regionally correlatable coal seams, and limestone beds are illustrated. **a.** Line 1. A broad group of coal seams is grouped into the Medicine River coal zone. Upper Medicine River (UMR) and Lower Medicine River (LMR) are seams (marked 1 and 2) recognizable basinwide. A very approximate progradational stacking pattern is apparent in the barrier sandstone bodies but internally within a sandstone body retrogradational patterns can be recognized. An initial backstepping and later prograding phase of the barrier formation is possible. Retrogradational arrangement of the three key limestone beds (in the Ostracode zone) can be clearly seen. **b.** Line 2. Splitting and merging patterns of the UMR and LMR (1 and 2) coal seams are shown. The barrier sandstone bodies lying between coal seam 2 and the topmost limestone horizon are thinner and no clear stacking pattern (a vague back-stepping pattern?) is recognizable. **c.** Line 3. The UMR seam (1) appearing as one at the SE end splits into three at the NW end. Barrier sandstone bodies at the NW end exhibit a vertical aggradational pattern. Limestone units are probably retrogradational. Deeper parts of the unconformity surface contain incised-valley fills.

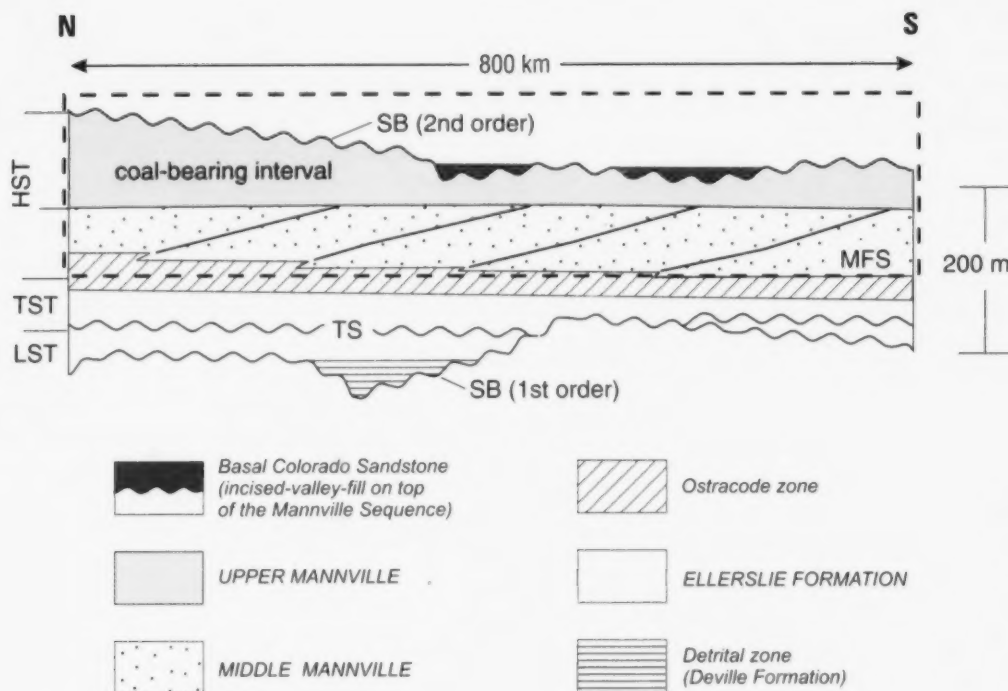


Figure 4. Sequence stratigraphy of the Mannville Group interpreted as a second-order depositional sequence. The cross-section is the one shown in Figure 1. Names of informal lithostratigraphic units are illustrated. Thickness of stratigraphic units are not to scale. SB = sequence boundary, TS = transgressive surface, MFS = maximum flooding surface, LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract. All coal seams are confined to the HST of the second-order sequence but in the scale of third-order and fourth-order sequences most of them belong to the TST.

a paleogeographic and paleoenvironmental reconstruction of the Upper Mannville strata; and 5) construct a sequence stratigraphic coal depositional model.

The basic sequence stratigraphic model for paralic coal was then applied to a detailed study of the Upper and Lower Medicine River (UMR and LMR) seams and the G seam, which was previously named the post-Glauconitic coal zone by Strobl (1988). This study helped in further elucidating the different parameters of the model.

ACKNOWLEDGMENTS

E. Davies is gratefully acknowledged for providing a summary of the palynological work.

During the initial phase of the study, K. Hage assisted in examination of cores, construction of subsurface cross-sections, and field studies. Her valuable help is also gratefully acknowledged. The manuscript was critically read by colleagues at the Geological Survey of Canada (Calgary).

We acknowledge V. Stasiuk, J. Dixon, and J. White, all of whom made many valuable suggestions for improvement. W.J. McDougall and A.F. Embry reviewed the coal seam stratigraphy and the sequence stratigraphy, respectively. C. Boonstra drafted many figures and B. Rutley did the photographic work.

The authors wish to thank K. Pratt for producing the image analysis plots of the coal blocks and are grateful to D.L. Marchioni of Petrologic-Services, Calgary for maceral analyses on coal blocks and grain mounts.

CRETACEOUS COALS OF THE WESTERN INTERIOR SEAWAY

Over the past two decades, stratigraphic analysis of coal-bearing strata of the Western Interior Seaway of North America has indicated a close relationship between maximum development of thick coal deposits and transgressive-regressive cycles (Kauffman, 1980; Lawrence, 1982; Ryer, 1981, 1984; Cross, 1988; McCabe and Shanely,

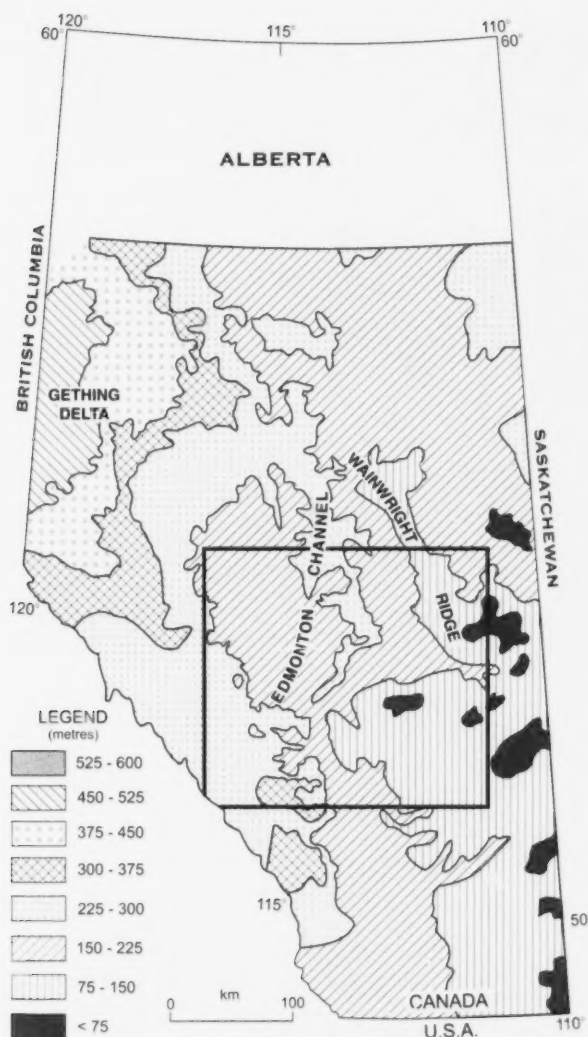


Figure 5. Regional isopach map of the Mannville Group. Broad paleotopographic features are named. The boxed area is the area of study. A northwesterly thickening trend characterizes the Mannville strata.

1992; Bustin and Smith, 1993). The integrated data have resulted in a model in which the peak of coal deposition takes place at the transgressive maximum of a third-order sea-level cycle, where thick sandstones representing fourth-order cycles are vertically stacked (Ryer, 1984; Cross, 1988).

In the Western Canada Sedimentary Basin (WCSB), the Lower Cretaceous coals of the Gates Formation, which are the outcrop equivalent of the Mannville coals studied here (Fig. 2), have also been correlated with the transgressive maximum of a second-order sea-level cycle (Moosebar-Clearwater transgression) but only in a general way (Bustin

and Smith, 1993) and without relating the coal seams either to high-frequency sea-level cycles or to stacking patterns of parasequences in the coal-bearing strata. Kalkreuth and Leckie (1989) described a 50 m thick "coarsening-upward" prograding shoreline sequence, which could represent a high-frequency sea-level cycle of perhaps fourth-order.

Regional stratigraphy

As shown in the subsurface cross-sections in Figure 3, the regional stratigraphy of the Mannville Group suggests shoreline sedimentation in a prograding barrier coastline. The stratigraphy is broadly comparable to the dip-section of the back-barrier coals of the Appalachian coal basins originally illustrated by Ferm et al. (1971) and modified by Galloway and Hobday (1996, p. 364). A carbonate interval containing three limestone beds close to the second-order maximum flooding surface (MFS) (Fig. 3) divides the lower Mannville transgressive strata from the prograding, coal-bearing upper Mannville strata. Toward the top, more and more incised valley-fill deposits interrupt regional coal seams, indicating increasing influence of fluvial sedimentation.

Regionally, five major coal seams (>2 m) can be traced for more than 100 km (Fig. 3). An interesting aspect of the stratigraphic architecture of these seams is the pattern of their splits. In general, all major seams and the two Medicine River seams in particular, split progressively basinward in a northwest direction. Formed under similar circumstances behind stacked barriers, lignites of the Oligocene-Miocene Morwell Formation of Australia (Holdgate and Sluiter, 1991) also exhibit splitting by numerous mudstone partings that represent minor marine transgressions. Apart from splitting, the major Mannville coal seams also have been cut by incised valley-fills (Fig 3).

Paleogeography

In the deeper pockets of the sub-Mannville unconformity, a chert breccia representing a residual paleosol known as the Detrital zone is preserved (Fig. 7). Elsewhere, the early infilling of the Mannville basin is represented by the Ellerslie Formation, which formed when incised valleys on the basal unconformity surface were filled with conglomeratic channel lags and cross-stratified fluvial strata. This was followed first by bioturbated, marginal-marine, storm-generated strata and later by tidal-delta sediments (Banerjee and Davies, 1988). At the peak of the transgression, storm sediments with graded beds or combined-flow ripples were deposited during the Ostracode zone sedimentation, culminating in the deposition of subtidal dolomitized limestone horizons marking the maximum flooding surface. This was followed by progradation of the

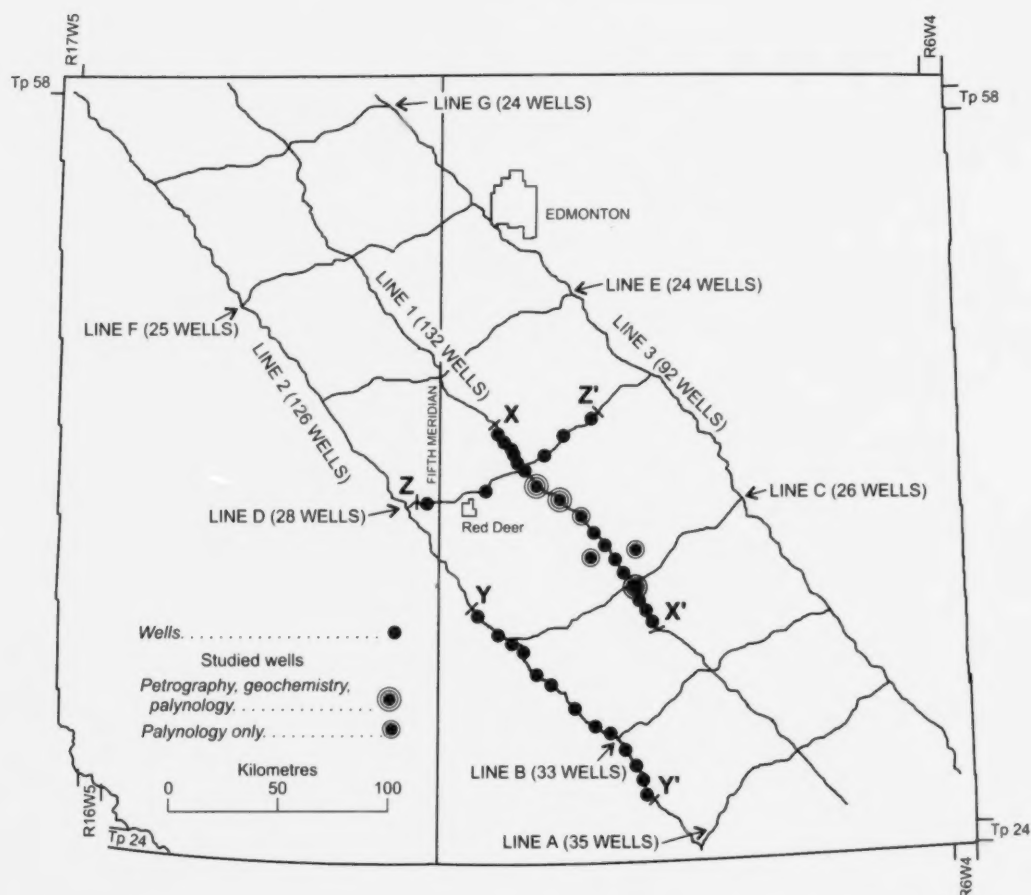


Figure 6. Enlarged view of study area. Locations of the three strike sections (1, 2 and 3) and seven dip sections (A–G) are shown. Regional stratigraphy is based on these cross-sections compiled from correlation of geophysical logs in 545 wells. XX', YY' and ZZ' are the locations of section lines in Figure 9a, b and c, respectively. Wells used for the detailed coal studies are circled.

shoreline. Above the limestone marker, the barriers (Chiang, 1984) (Fig. 3), which probably formed during transgression, were part of the progradational wedge that advanced basinward (NW). Backfilling of the lagoon behind the barrier produced a progradational platform over which extensive coal swamps could form. Repeated fluctuations of the sea level produced several packages of coal-bearing strata separated by high-frequency sequence boundaries (Banerjee et al., 1996). The detailed delineation of these fourth-order sequences is described in a later section.

Lithostratigraphy and lithofacies of the coal-bearing strata

Since oil and gas do not occur in the upper coal-bearing intervals (Fig. 8, 9) of the Mannville, very few cores of the strata immediately adjacent to the major coal seams exist. Of the 114 cores examined in this study only seven or eight are

close to the LMR seam. The majority of the cores belong to the Eilerslie-Ostracode-Glauconitic Sandstone interval, lying below the coal seams. However, an examination of the sedimentary facies of this interval is useful because, first, there is a minor coal seam horizon present (G seam, see Fig. 8, 9) that has been penetrated by many cores, and second, because strata immediately below the major coal seams could provide important paleoenvironmental information.

A detailed description of sedimentary facies in these intervals follows.

Lower Mannville subgroup (10–80 m)

The Lower Mannville subgroup ranges from the basal unconformity to the top of the Ostracode zone (Fig. 8), and contains the following units:



Figure 7. Core photograph showing sub-Mannville unconformity (arrow), which is a first-order sequence boundary separating swirly-bedded Detrital zone (Dz) rocks with vuggy angular chert clasts and rare crinoid stems set in a greenish muddy matrix from the Banff Formation (Bf), consisting of laminated white grainstone with green mudstone layers. Pyrite disseminations occur in both units. The contact is sharp and undulatory. Well 8-11-33-18W4 between depths 1287.6–1290.8 m (GSC Photo no. 4609-27).

The Detrital zone (Denville Formation)

Locally at the deepest parts of the unconformity surface, occurs a zone of unusual lithologies (Fig. 1c) comprising: a chert breccia with angular chert clasts (Fig. 7) set in a kaolinitic muddy matrix; a structureless, fine-grained, kaolinitic sandstone mottled with sphaero-siderites; and a laminated greenish to greyish mudstone with soft-sediment

deformation that occurs directly over a lime mudstone belonging to the Mississippian Banff Formation. These strata (5–10 m) represent a mixture of weathering residues of carbonate rocks, burrowed marine mudstone and debris-flow deposits.

Ellerslie Formation

This formation consists of retrogradationally stacked, coarsening-upward (CU) sequences containing black shale, fine-grained, burrowed sandstone, crossbedded sandstone with mud-drapes, crosslaminated sandstone with mud couplets, and tidal rhythmites (Banerjee, 1986). Rare coquina beds also occur in the basal parts. Where the Ellerslie lies directly over the unconformity surface, particularly in the extreme northwest where it overlies Jurassic rocks, three facies types are present: a thin (0.3–0.5 m) basal (transgressive?) lag of well rounded quartz granules in a well-sorted, fine-grained sand matrix; a thin (0.2–0.3 m) condensed zone of fine-grained green sandstone with a high glauconitic content; or a bored hardground of the *Glossifungites* facies with the Jurassic shale below.

The following lithofacies (Fig. 10) occur in the Ellerslie Formation:

1. Thick, fining-upward (FU) successions (10–12 m) with crossbedded, fine- to medium-grained, burrowed sandstone with a few mud-draped foresets overlying a basal zone of pebble-sized mud clasts with a sharp contact with the shale below. These have been interpreted as tidal channel or inlet deposits.
2. Thin, FU successions (3–4 m) of interbedded burrowed sandstone and shale exhibiting inclined heterolithic stratification (IHS). These also are interpreted as tidal channel deposits (Fig. 10, 11a).
3. Thick, CU successions (10–15 m) with sharp tops, consisting of burrowed, lenticular-bedded, very fine-grained sandstone grading upward into thickly crossbedded, medium-grained sandstone with mud drapes. These have been interpreted as tidal delta deposits (Banerjee and Davies, 1988).
4. Thin, CU successions (1–2 m) of fine-grained, moderately to intensely burrowed (*Asterosoma*, *Chondrites*, *Cylindrichnus*, *Gyrolithes*, *Palaeophycus*, *Planolites*, *Skolithos*, *Teichichnus*, *Thalassinoides* and rare *Zoophycos*), wave-, or combined-flow, ripple-laminated sandstone sharply overlain by organic-rich black shale. These have been interpreted as either storm-deposited shallow-marine deposits or storm washover sediments in a back-barrier lagoon.
5. Thin (1–2 m), grey or black shale, rarely with sideritic mudstone and siltstone lenses with scattered shell layers. These are interpreted as lagoonal mudstone.

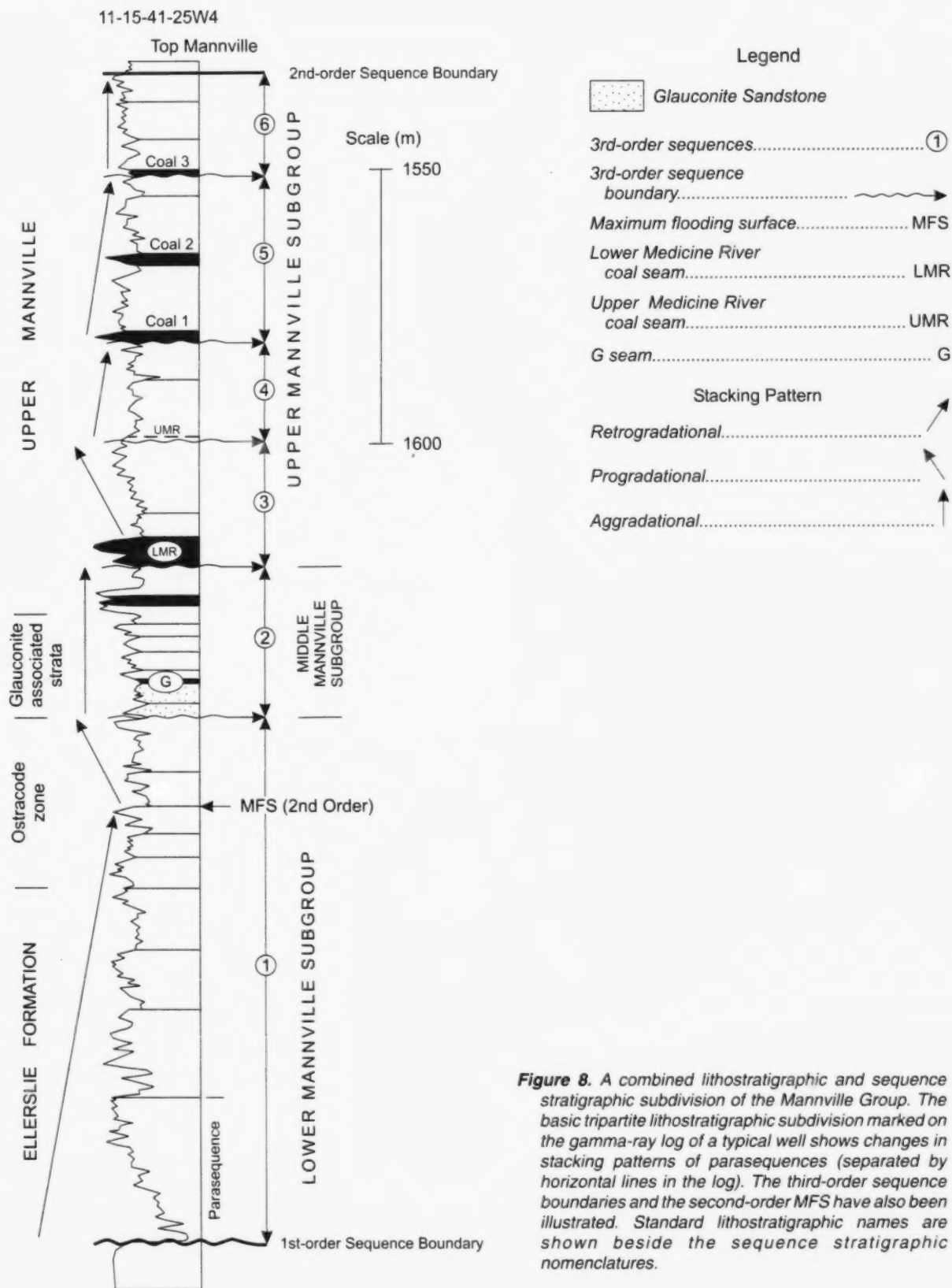


Figure 8. A combined lithostratigraphic and sequence stratigraphic subdivision of the Mannville Group. The basic tripartite lithostratigraphic subdivision marked on the gamma-ray log of a typical well shows changes in stacking patterns of parasequences (separated by horizontal lines in the log). The third-order sequence boundaries and the second-order MFS have also been illustrated. Standard lithostratigraphic names are shown beside the sequence stratigraphic nomenclatures.

6. Thin (1–2 m), CU successions of lenticular- to flaser-bedded, burrowed, fine-grained sandstone interpreted as tidal flat sediments.
7. Thin (<0.5 m), rhythmically bedded sandstone and shale with rare burrows. These are interpreted as tidal rhythmites in a lagoon-tidal flat environment.

The Ellerslie Formation (Fig. 10) is dominantly composed of burrowed, fine-grained sandstone (Facies 1, 2, 6) and black shale (lagoon and tidal flat sediments; Facies 6, 7) in which thicker, crossbedded sandstone (Facies 1, 3; tidal deltas and channels) are encased. This sequence is punctuated with rare incursions of open-marine sediments (Facies 4, 5).

The Ostracode zone

The Ostracode zone contains thin, regionally extensive limestone beds marking basin-wide flooding events accompanied by starvation of clastic sediments (Fig. 3a, b, c; 9a, b, c). Characterized by a *Cruziana* trace fossil assemblage (Banerjee and Raychaudhuri, 1996) and containing up to twenty species of dinoflagellates and two to five species of foraminifers, the Ostracode zone represents the peak of marine transgression in the Mannville sequence.

Lithofacies in this zone are represented by:

1. Two to three metre-thick, organic-rich, laminated, pyritic black shale beds with rare siltstone lenses (lenticular-bedded) and interpreted as very shallow-water, restricted-marine sediments. Within many of these shale units molluscan shell beds occupy flooding surfaces either at the bases of parasequences (Banerjee and Kidwell, 1991) or at their tops. These represent hydraulic sorting events in a shallow sea.
2. Dolomitized lime mudstone deposits, which are areally extensive and may exhibit emergence features (Fig. 12a, b, c). These are overlain by strata representing maximum flooding events within the overall transgressive scenario.
3. CU successions (2–5 m) of burrowed, fine-grained sandstone with wave-ripple or combined flow-ripple laminae (Fig. 11b). These are multiple-event, storm-generated, open-marine sediments.
4. Graded beds of shell debris, 1–2 cm thick. These also are storm-generated beds recording brief, rapid, single depositional events.

In the Ostracode zone, a lower (Fig. 8) retrogradational stacking pattern changes above the maximum flooding surface, indicating an initial deepening trend followed by a shallowing one.

The lithofacies successions, from fluvial, to tide-dominated, to storm-dominated sedimentation, also record a

deepening trend from the sub-Mannville unconformity up to the maximum flooding surface.

The Middle Mannville subgroup (20–30 m)

The Middle Mannville subgroup extends from the top of the Ostracode zone to the base of the LMR coal seam. This is the third-order Sequence 2, and includes the Glauconitic Sandstone member and the "Glauconitic coal zone" (G seam) of previous authors (Strobl, 1988).

The unconformity at the base of this unit lies directly above the topmost limestone in the Ostracode zone (Fig. 12a). At this boundary, the sequence boundary and the transgressive surface coincide. The unconformity, the flooding surface and the transgressive lag can all be identified. The overlying sediments are sparsely to moderately burrowed with a *Cruziana* ichnofacies assemblage (*Asterosoma*, *Palaeophycus*, *Planolites*, *Skolithos*, *Teichichnus*).

The Glauconitic Sandstone

Although this name has been used as an informal lithostratigraphic term, it is rather confusing because the sandstone normally does not contain any glauconite; it includes strata of at least two different lithofacies, one a prograding shoreline sequence (Rosenthal, 1988; Brownridge and Moslow, 1991) and the other an incised-valley fill (Wood, 1996); and the above two lithofacies are separated by a sequence boundary. The term Glauconitic Sandstone will not be used in this study but the part of the Middle Mannville strata lying between the topmost Ostracode limestone and the base of the G seam (the stippled part in Fig. 8) is equivalent to the Glauconitic Sandstone of previous authors. Basically, the Middle Mannville subgroup consists of three to five CU successions separated by sharp planar surfaces (parasequences?). Three facies can be recognized:

1. Black shale (2.0–2.5 m) underlying, with sharp contact a 0.5–0.6 m coaly zone (the G seam), which in turn is overlain by laminated, burrowed black shale (Fig. 13). A tidal flat-lagoon-coastal mire environment is interpreted.
2. CU units, 8–10 m thick with burrowed, lenticular-bedded (wave- and combined-flow-ripple laminae) shale and sandstone at the base (Fig. 11d) and a 2–4 m thick, crossbedded, medium- to coarse-grained sandstone at the top, which may show tidal features such as mud-draped foresets, rare mud couplets (Fig. 11c) and rare, IHS-type bedding. A tidal inlet or tidally influenced fluvial channel environment is indicated.
3. Shale beds, 3 to 4 m thick, interbedded with crosslaminated, fine-grained sandstone. The sandstone

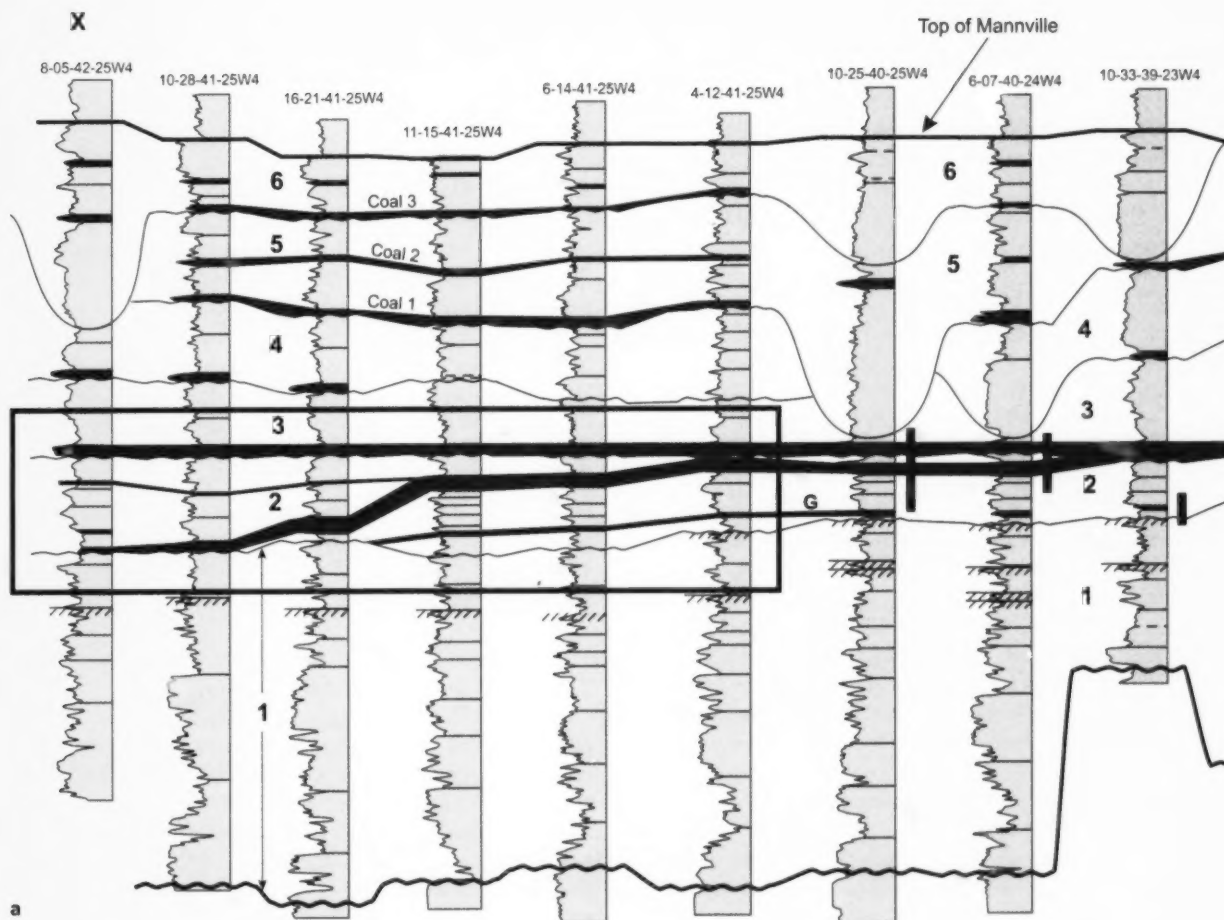


Figure 9a. Cross-section along line XX' in Figure 6 (strike section). **a, b, c.** Sequence stratigraphic framework of the Mannville Group based on subsurface correlation of geophysical logs (gamma-ray and density). Six third-order sequences were recognized within the Mannville. These are separated by five sequence boundaries. The sub-Mannville unconformity, because of its large time-gaps at places (up to 100 Ma) is considered a first-order sequence boundary (Embry, 1995) and the Mannville-Colorado Group sequence boundary (top), is considered a second-order one (Banerjee et al., 1994). The third-order sequence boundaries were selected on the basis of: 1) changes in the stacking pattern of parasequences from progradational to retrogradational upward at the top of sequence 1; 2) presence of incised-valleys on top of sequences 3, 4 and 5; and 3) presence of key beds of limestone with emergence features at the top of sequence 1. Earlier sequence boundaries might be eroded by later ones. Coal seams overlie sequence boundaries or are close to them and drape over incised-valley fills (see sequences 3, 4 and 5). Informal stratigraphic units, the Ellerslie Formation and the Ostracode zone are parts of Sequence 1. The Glauconitic Sandstone member belongs to Sequence 2.

has no grain size trend, contains few burrows, and is lenticular bedded or parallel-laminated in mm-scale. This facies exhibits soft-sediment deformation, and commonly contains rootlets and plant fragments. The strata are interpreted as coastal mire (coal) and lagoonal sediments (shale on top, shale and sandstone at the bottom) with paleosol development below the coal seam (see uc in Fig. 14).

The Upper Mannville subgroup (100–120m)

The Upper Mannville subgroup extends from the base of the LMR seam to the top of the Mannville Group (Fig. 8). It includes all the major coal seams in the Mannville Group and contains incised valley-fill sediments indicating fluvial influence (Fig. 3). Stratal patterns that become aggradational toward the top (Fig. 8) corroborate this.

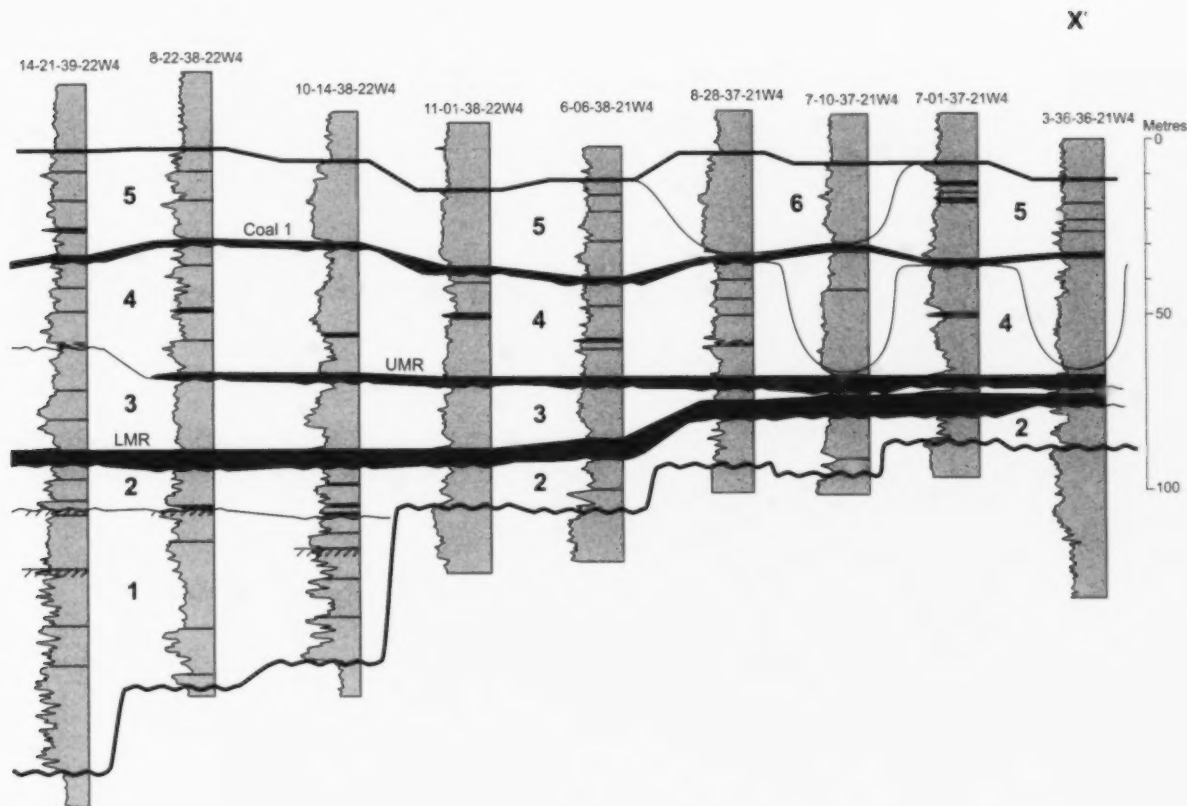


Figure 9a continued.

One example of a thick (10–15 m), uniform sandstone occurring as incised-valley fills characterized by blocky gamma-ray log signatures is illustrated in Figure 15 where the valley has eroded the G seam. A layer of coal clasts line the erosional surface. The sedimentary succession consists of alternating crossbedded, and lenticular-bedded, fine-grained sandstone and layers of mudclasts. A fluvial environment is suggested.

Paleoenvironmental evolution and the coal-forming environment

The record of cored intervals suggests the following trend in the paleoenvironmental evolution of the Mannville Group. During an initial rise of sea level, incised valleys on the sub-Mannville unconformity surface were filled in their deepest parts with fluvial sediments (Detrital zone, Lower Ellerslie).

With continued marine inundation, large embayments were formed and filled with marginal-marine sediments (Upper Ellerslie, Ostracode zone). The peak of marine transgression was reached during deposition of the middle "Ostracode zone" with some open-marine sediments. Progradation followed after barrier islands formed at the northwestern basinward end (Glaucinitic Sandstone) and back-barrier basins were filled with lagoon, tidal-flat, tidal-delta, and tidal-channel sediments.

During this backfilling stage, large coastal mires were formed and episodes of high-frequency sea-level fluctuations were recorded by coal seam splits bounding progradational wedges, when the thinner, and less extensive coal seams were formed. Later, when the back-barrier basin was almost filled, a coastal plain with a network of tidally influenced fluvial systems became the site of thicker, more extensive coal seams.

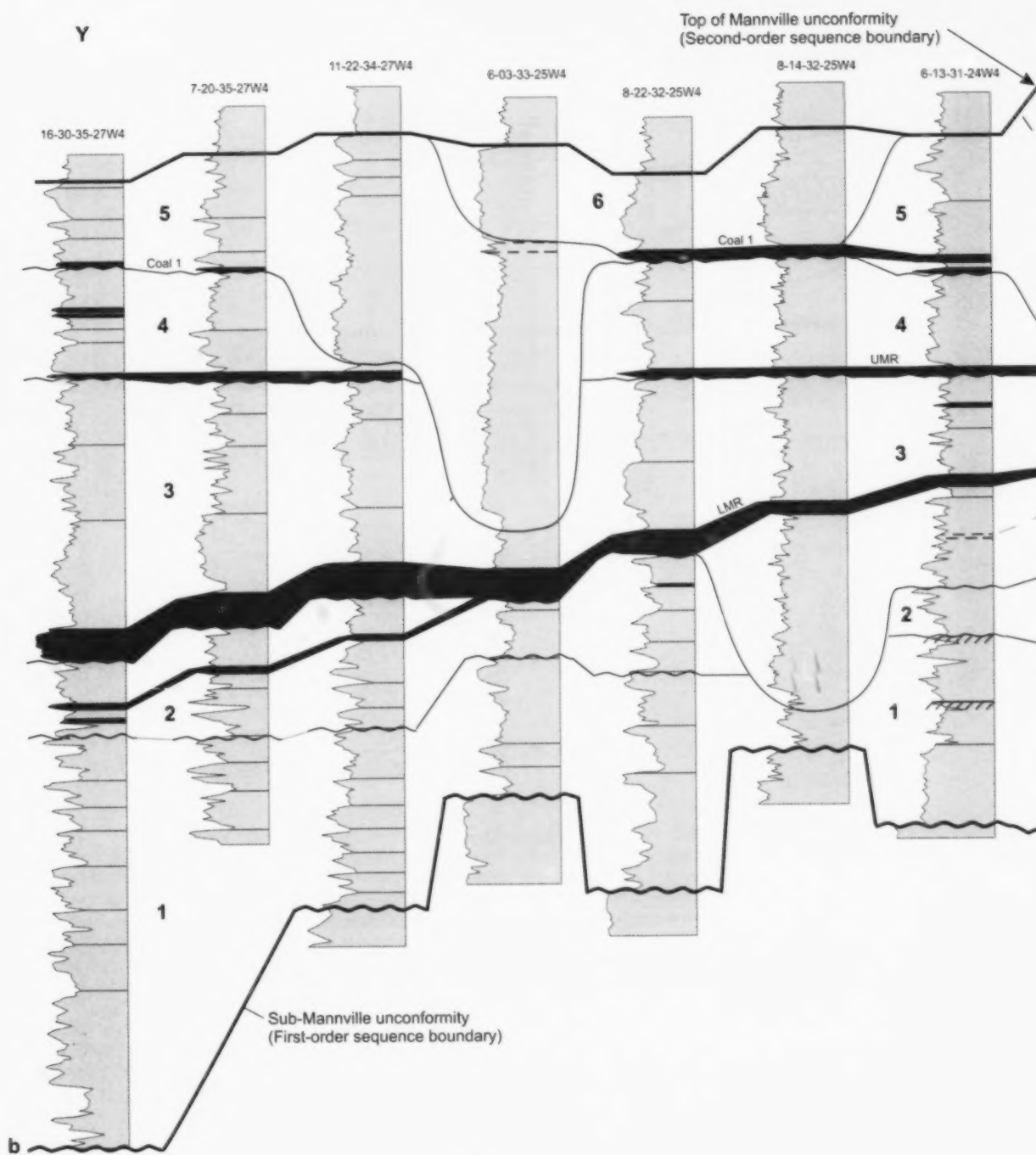


Figure 9b. Cross-section along line YY' in Figure 6 (strike section).

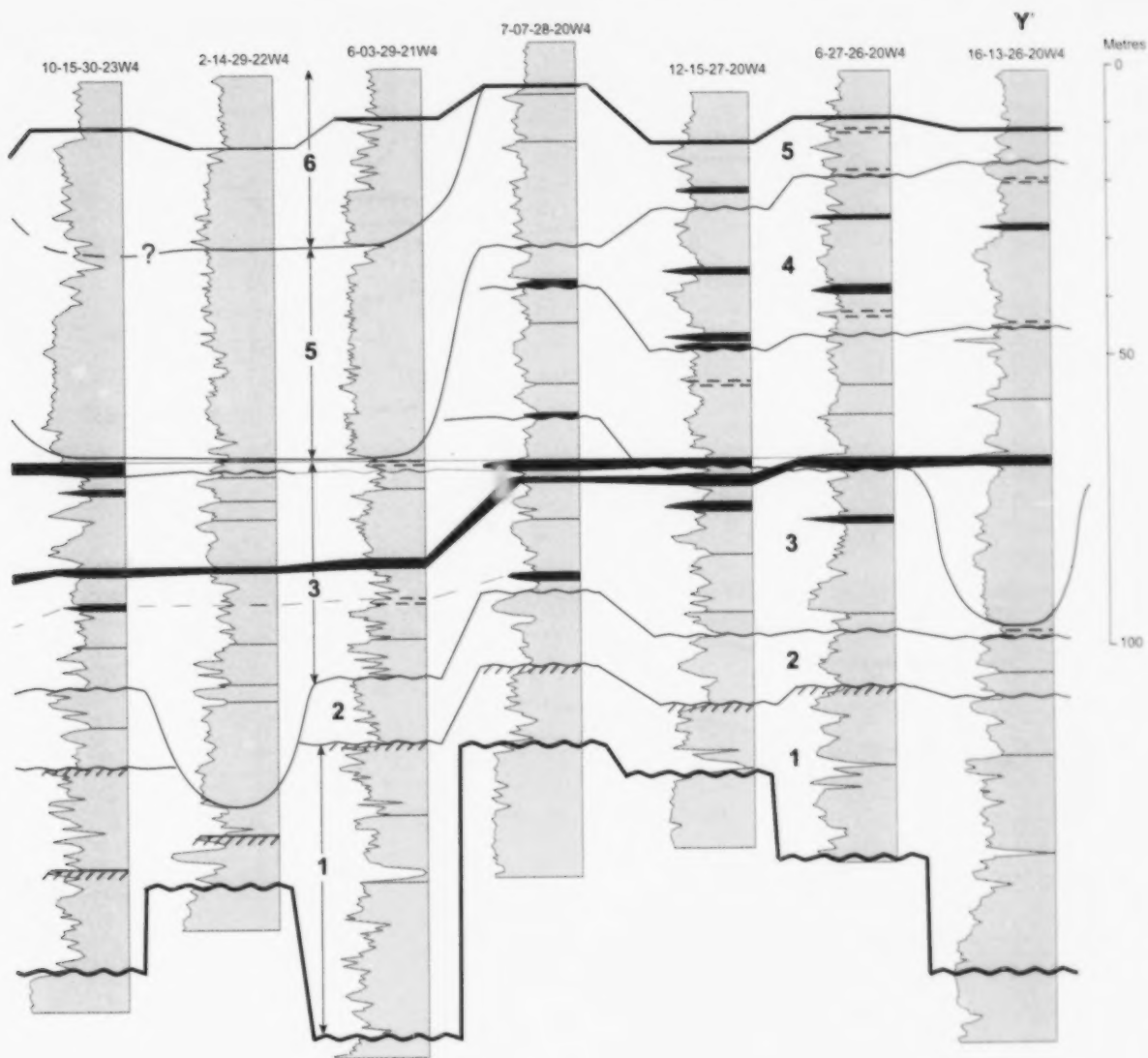


Figure 9b continued.

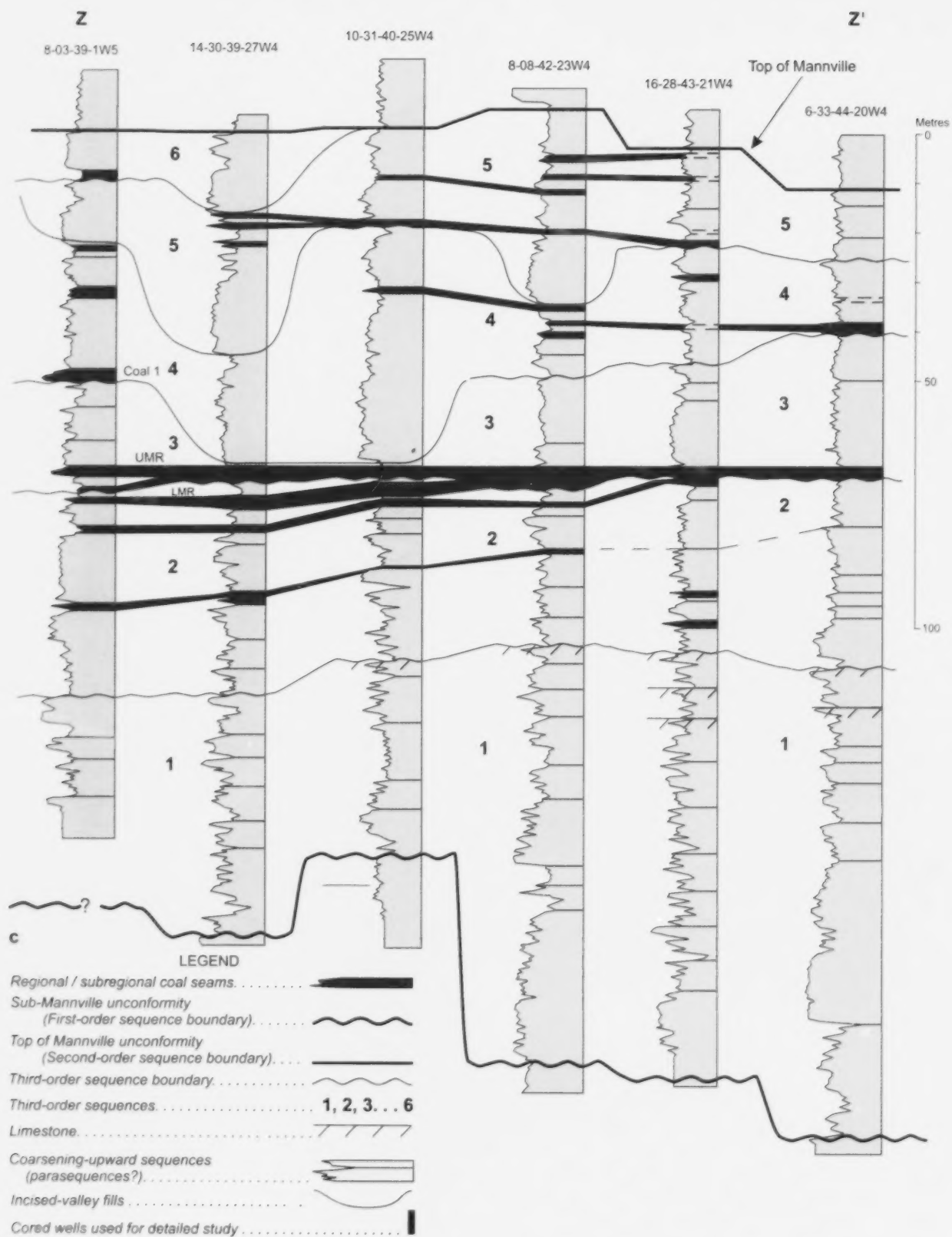
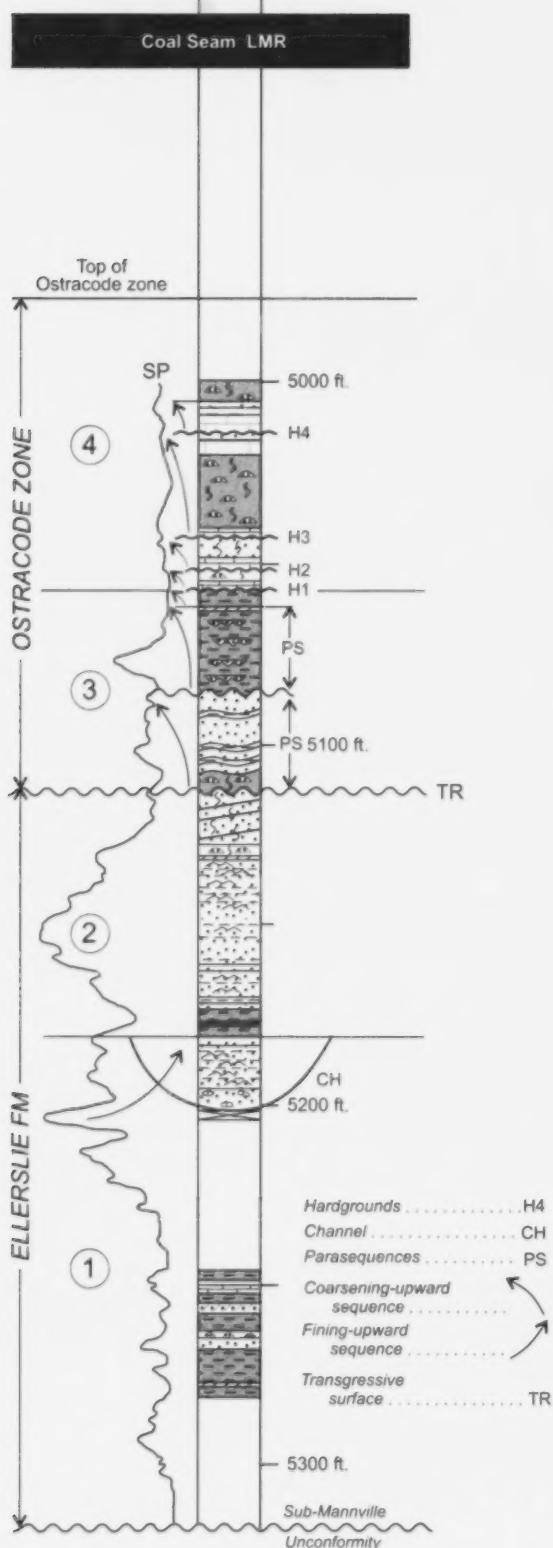


Figure 9c. Cross-section along line ZZ' in Figure 6 (strike section).

11-8-41-24W4

LEGEND



	Coal		Sandstone
	Coal clasts		Siltstone
	Shale		Limestone
	Mud clasts		Siderite

Shell beds	
Crossbedding	
Lenticular bedding	
Wavy bedding (wave-, combined-flow-ripple lamination)	
Flaser bedding	
IHS (Inclined heterolithic stratification)	
Burrows	
Crosslamination (current-ripple lamination)	
Crosslamination (wave-ripple lamination)	
Roots	
Pyrite	
Chert clast	
Wood fragments	
Deformation	
Loaded contact	

Figure 10. SP and lithological logs of the cored interval of the Lower Mannville subgroup (see Fig. 8). A long (approx. 60 m) core exhibits: 1) a prominent transgressive surface (TR) at the contacts of the Ellerslie and Ostracode units; 2) tidal features (IHS, mud-draped foresets) in the Ellerslie channel sediments just below TR; 3) a fining-upward, overall grain-size trend; and 4) a Cruziana ichnofacies trace fossil assemblage (Banerjee and Raychaudhuri, 1996) and 20 species of dinoflagellates in the Ostracode zone indicating a deepening shallow-marine environment. Details of the sedimentation in this interval have been discussed in Banerjee and Davies (1988) and Banerjee and Kidwell (1991).

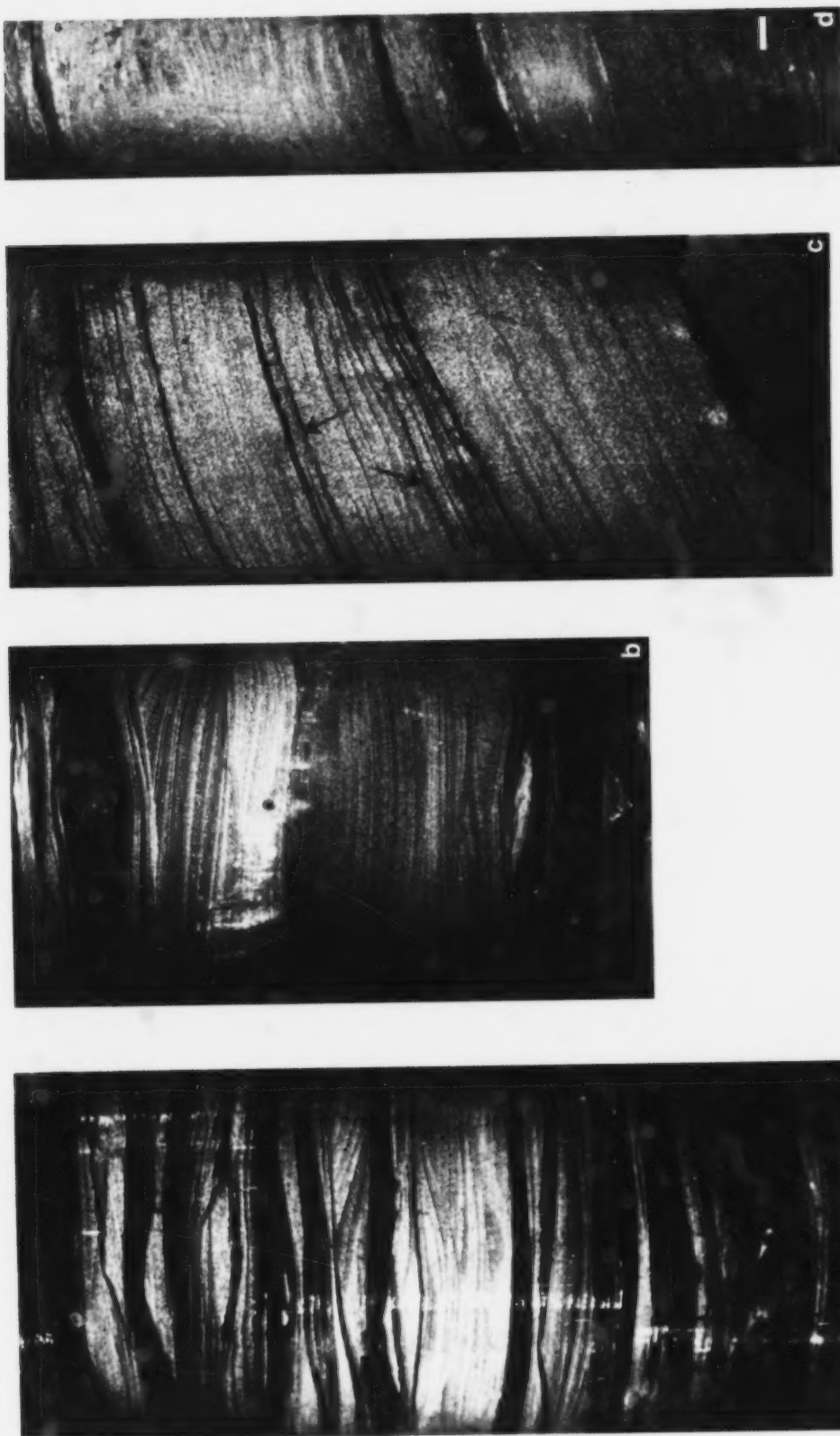


Figure 11. Wave- and tide-generated structures in the studied sequences. **a, b, c** are in the same scale; bar in **d** is 1 cm. **a.** Inclined heterolithic stratification (IHS) with internal crosslamination in the topmost part of Ellerslie Formation (see Fig. 10). Rare burrowing. Well 11-8-4-24W4, depth 5116–5118 ft. (GSC photo no. 4609-36). **b.** Fine-grained sandstone showing micro-HCS. Top part of Ostracode zone below the top limestone layer. Well 11-34-24-18W4, 1349.9–1350.0 m (GSC photo no. 4609-39). **c.** Mud-draped foresets in a medium-grained tidal sandstone showing also mud-couplets (arrows) and reactivation structure (R). Glauconitic Sandstone equivalent. Well 6-24-37-23W6, depth 1500–1501 m (GSC photo no. 4609-32). **d.** Basal part of a coarsening-upward sequence showing wave- and combined-flow-ripple-lamination located above the Ostracode zone. Glauconitic Sandstone equivalent. Burrows and syneresis cracks are also present. Well 14-35-38-23W4, depth 1422–1423 m (GSC photo no. 4609-10).

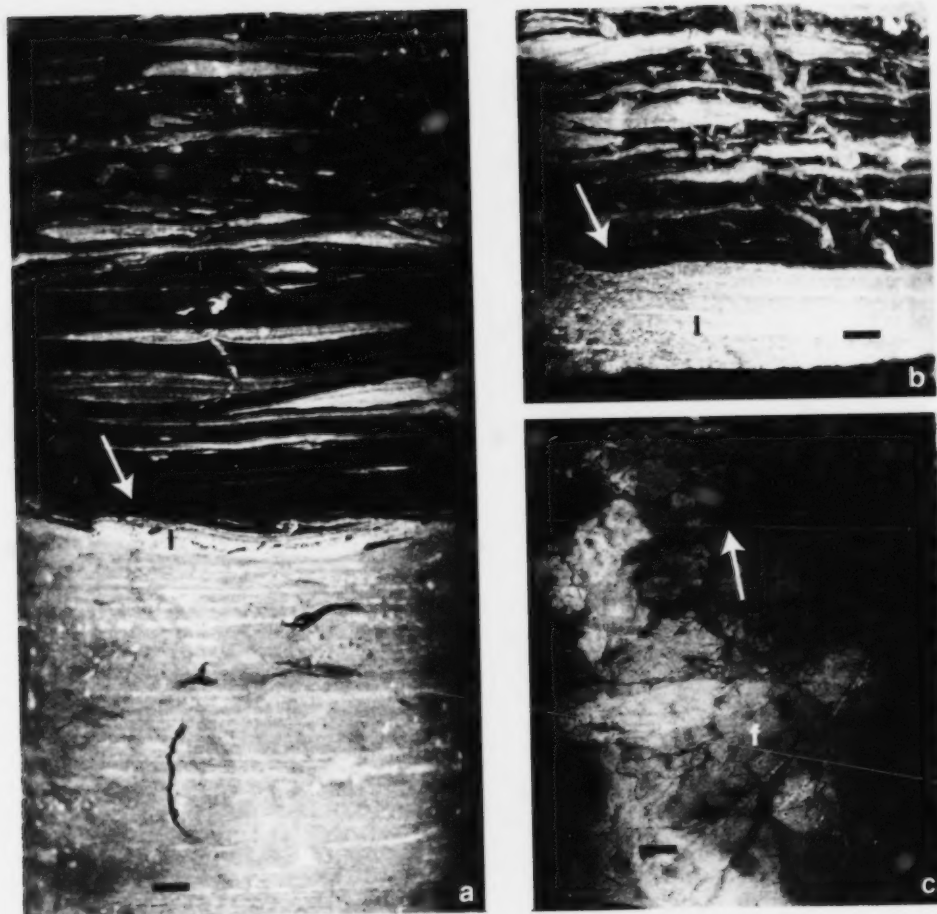


Figure 12. Core photograph of the third-order sequence boundary at the top of the Ostracode zone (see Fig. 9). **a.** Dolomitized lime mudstone with emergence features (roots?) overlain by a cm-thick ripple-laminated basal granule lag (l) defining the sequence boundary (arrow). Overlying heterolithic layer is lenticular-bedded, burrowed and shows syneresis cracks. Well 14-35-38-23W4, depth 1428–1429 m (GSC Photo no. 4609-35). **b.** The same boundary (arrow) with similar lithologies showing the laminated basal lag layer (l) and similar heterolithic lithology of the overlying unit. Well 6-7-40-24W4, depth 1584 m (GSC Photo no. 4609-28). **c.** The same boundary with a coarser lag (l) which passes on to a fractured (f), dolomitized lime mudstone and then to a laminated, argillaceous lime mudstone (not shown) below (GSC Photo no. 4609-40). All bars present are 1 cm. Well 7-3-39-154, 1134.3 m.

The paralic nature of the Mannville coals

The overall compositional nature of the Mannville coals, including the presence of visible disseminations of pyrite in the coal and a mixed miospore assemblage of freshwater, brackish water and rare marine algal cysts in the coal seam, as well as the lithological characters of the adjacent sedimentary strata, indicate overwhelmingly their coastal nature. The assemblage includes both marine (*Subtili-*

sphaera, *Pseudoceratium*, *Odontochitina*) and euryhaline dinoflagellates (*Holmwoodinium*, *Breodoxella*). The high sulphur (>2%) content of some coal layers and the marine character of the shale partings corroborate this interpretation.

The shale partings and roof rocks are characterized by highly burrowed sandstone and burrowed, pyritic black shale and the presence of rare marine dinoflagellates. The presence of marine trace fossils (Fig. 16a, b, c) in the coal-

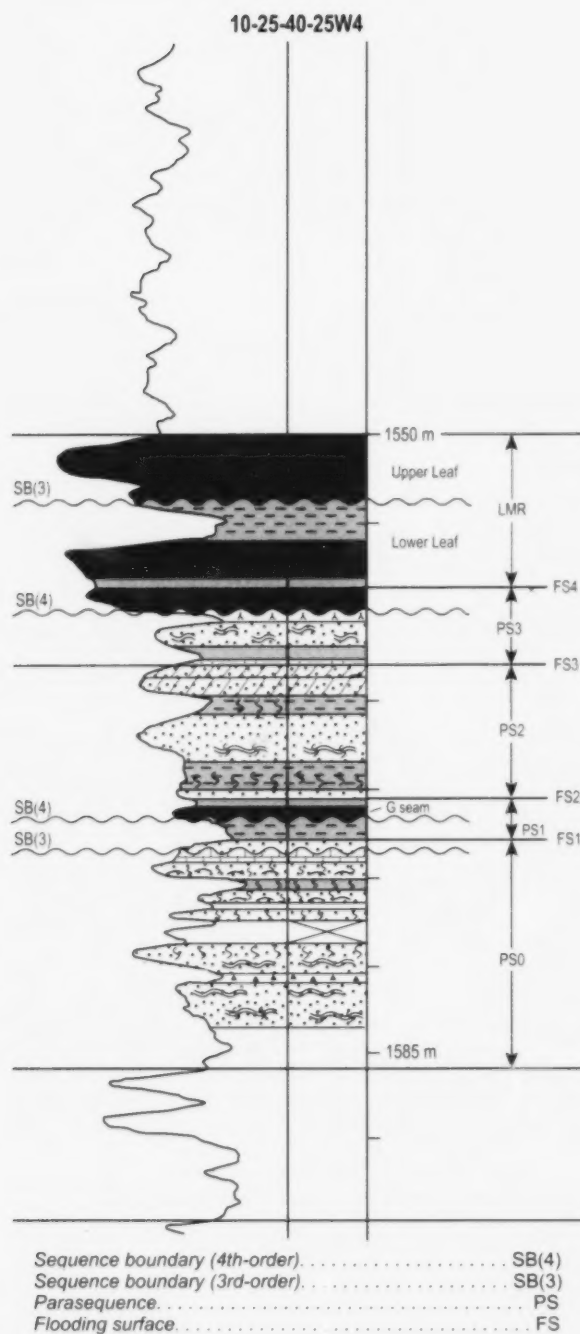


Figure 13. Lithology log of the cored interval in well 10-25-40-25W4, which penetrated the lower leaf of the split LMR seam and the entire G seam. Flooding surfaces (FS) are marked by: 1) cm-thick shell lag over brecciated, dolomitized lime mudstone overlain by black organic-rich shale (FS1); 2) black, pyritic shale overlying coal seams (FS2 and 4) or black mudstone sharply overlying thick (>1.0 m), fining-upward, cross-bedded, tidal channel sandstone (FS3). There is a change in the regime of sedimentation from the wave-dominated interval below FS1, to the tide-dominated one above. For legend, see Figure 10.

bearing strata (*Arenicolites*, *Asterosoma*, *Chondrites*, *Cylindrichnus*, *Palaeophycus*, *Planolites*, *Skolithos*, *Teichichnus*) also distinctly indicates a marginal-marine setting.

Because coal deposition occurred close to the shoreline, frequent flooding by seawater was common. Even during periods of overall regression, sporadic flooding could have occurred. Brief periods of emergence and dryness could also have occurred during transgression.

THE MANNVILLE GROUP AS A SEQUENCE

Based upon a hierarchical system suggested by Vail et al. (1991) and modified by Embry (1995), the Mannville Group within Alberta is a second-order siliciclastic depositional sequence (Fig. 3). Using the criteria suggested by Embry (1995), the unconformity at the base of the group can be demonstrated to be a first-order sequence boundary in the WCSB because it is basin-wide in extent, and in most of the study area, it represents a major time gap (210 Ma) between the Mississippian carbonate below and the Lower Cretaceous siliciclastic strata above. The minimum time gap (20 Ma) is at the extreme northwest end of the study area where the Mannville overlies the Jurassic Fernie Group (Fig. 3a). Also, the Mannville Group is the second clastic wedge (Cant and Stockmal, 1989) in the Alberta foreland basin, recording a major tectonic event of uplift and erosion, and a major change in the sedimentary regime, from predominantly marine to predominantly continental.

To determine the hierarchical position of the sequence boundary (unconformity) at the top of the Mannville Group, that is, at the base of either the Joli Fou Shale or the Basal Colorado Sandstone (Fig. 1c, 3) the following criteria were used:

1. It is basin-wide in extent, representing a drop in relative sea level and incision at the boundary followed by a regional marine transgression (Banerjee et al., 1994).
2. It records a time gap of approximately 10 Ma, represented by four to five missing ammonite zones (Banerjee et al., 1994).
3. It records the initiation of a major, basin-wide marine transgression, the Kiowa-Skull Creek second-order marine cycle of the Western Interior Seaway (Caldwell et al., 1993).

However, since the Joli Fou-Mannville unconformity does not record either a major erosional and weathering interval or an important tectonic event and because it has a time gap shorter than that of the basal one, it is considered to be a second-order sequence boundary.

The order of a sequence is determined by the highest order of its boundaries (Embry, 1995), consequently the

Mannville Group should be considered a second-order sequence. The time span of the Mannville (~18 Ma) also matches that of a second-order sequence. Although previously interpreted to be a third-order sequence (Banerjee and Kidwell, 1991; Cant and Abrahamson, 1996), the nature of the sequence boundaries, the time span, and the average thickness (>200 m) of the group indicate that a second-order classification is more appropriate.

SEQUENCE STRATIGRAPHY

Introduction

Lithostratigraphically, the Mannville Group comprises three informal subgroups (Jackson, 1984; Banerjee, 1990): the Lower Mannville subgroup, the Middle Mannville subgroup and the Upper Mannville subgroup.

This tripartite subdivision of the Mannville second-order sequence also is apparent by the differences in the stratal patterns of the subgroup (Fig. 8, 9). The Ellerslie Formation and the lower half of the Ostracode zone show a conspicuous thinning upward or retrogradational stratal pattern (see arrow in Fig. 8). This ends at the maximum flooding surface and is overlain by upper Ostracode zone strata with a progradational pattern. From core study, the maximum flooding surface is found to be on top of a thin (<0.5 m), extensive, dolomitized lime mudstone that records a hiatal surface. The sedimentary record of this part of the Lower Mannville extending from the sub-Mannville unconformity to the maximum flooding surface also exhibits a deepening trend. Based on these evidences, this interval has been interpreted as the transgressive systems tract (TST) of the second-order Mannville sequence (Van Wagoner et al., 1990) (Fig. 4). The lowermost part of the interval, comprising the Detrital zone (or Deville Formation, see Fig. 1c, 3) might represent a lowstand systems tract (LST). Overlying the maximum flooding surface, the topmost Lower Mannville shows a progradational pattern followed by an aggradational one in the Middle Mannville. In the Upper Mannville, a basal progradational pattern is followed by two, successive retrogradational patterns ending with an aggradational pattern at the top. This oscillating pattern (Fig. 8) in the Middle and Upper Mannville suggests a weak overall aggradation that conforms with increasing fluvial influences in the interval recorded by the presence of incised valley-fills and increasing coal deposition. This interval has been interpreted as the highstand systems tract (HST) of the second-order Mannville sequence.

Some clarification is needed about the use of the term "parasequence" (Fig. 8) in this study. The term has been used here for the convenience of describing, demarcating, and correlating identifiable stratigraphic units in geophysical logs and cores. When applied to geophysical logs it means

"coarsening-upward" (CU) units ending with a sharp-topped sandstone abruptly overlain by shale. The identification of a marine flooding surface as required by definition (Van Wagoner et al., 1990) is implied. In cores, the parasequences are identified by their CU nature, sharp top and a marine flooding surface overlain mostly by pyritic black shale (Fig. 14). In sequence stratigraphic hierarchy, the parasequence is equivalent to, although not identical to a fifth-order, or rarely, fourth-order sequence (Embry, 1995). Flooding surfaces are in most cases an expression of a high-frequency sequence boundary also coinciding with a transgressive surface.

Third-order sequences

Superimposed on the overall stratal pattern of the second-order Mannville sequence, there are patterns of higher-order sequences. Sequence boundaries can be suspected wherever there is an upward change in pattern from progradational (HST) below to retrogradational (TST) above (see boundaries at the top of sequences 1 and 3 in Fig. 8). Third-order sequences were delineated based on the evidence of stratal patterns, presence of incised valleys, and recognition of unconformities in cores.

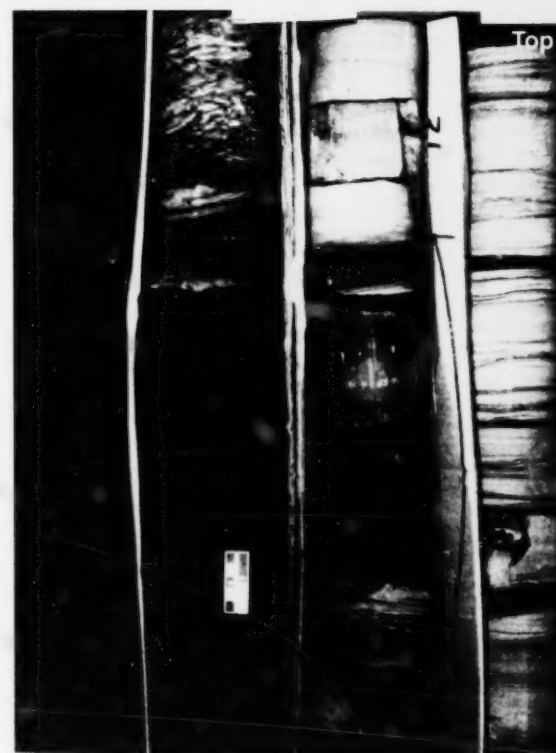
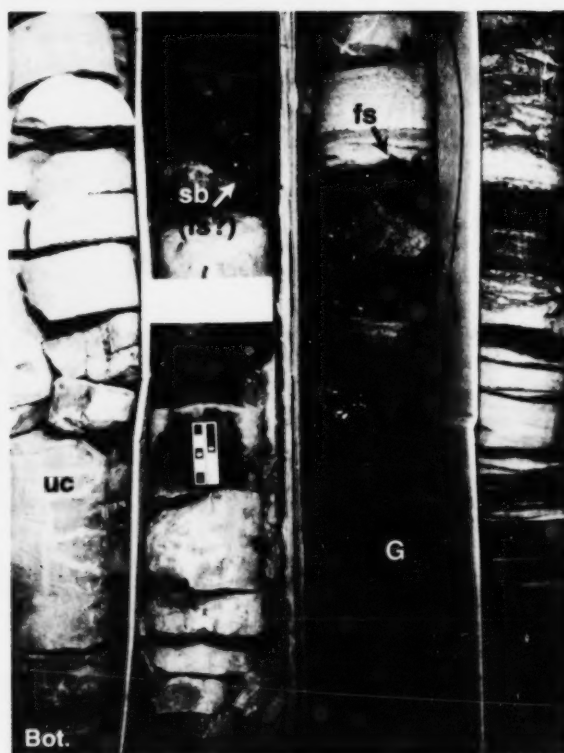
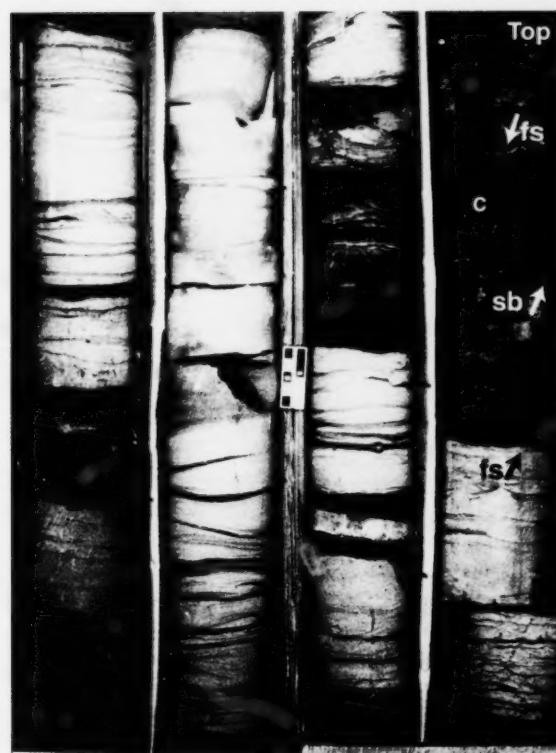
Regionally extensive incised-valley-fills suggest sequence boundaries (see tops of sequences 4 and 5 in Fig. 9a). Regional coal seams that drape over these incised valleys continue between the valleys overlying the interfluvial sequence boundaries (Zaitlin et al., 1994; Read, 1995).

Based on these criteria the Mannville sequence can be subdivided into six third-order sequences (Fig. 8, 9):

Sequence 1 extends from the sub-Mannville unconformity to the top of the Ostracode zone. The subtle change of stacking pattern from progradational to retrogradational at the top, and the presence of a limestone bed (Fig. 9, 12a, b, c), which shows evidence of emergence such as a desiccation breccia at the top with blackened pebbles, rootlets and a brown colour caused by oxidation (Fig. 12c). It is overlain by a thin, transgressive lag (Fig. 12a, b) recording the unconformity. This limestone underlies the sequence boundary at the top.

Sequence 2 extends from the top of the Ostracode zone to the base of the LMR coal seam. This stratigraphic interval contains the Glauconitic Sandstone. The sequence boundary at the base of sequence 2 is at the bottom of an incised-valley system (Fig. 9b). According to some authors (Strobl, 1988; Wood, 1996) the Glauconitic Sandstone occurs within this incised-valley-fill in Sequence 3.

Sequence 3 (boundary between 3 and 4 in Fig. 8) is recognized by an abrupt change in stacking pattern from



aggradational below to retrogradational above at the base of the UMR seam. This sequence extends from the base of the LMR seam to the base of the UMR seam (Fig. 9a, b, c).

Sequence 4 ranges from the base of UMR seam (absent in Fig. 8), which drapes over an incised-valley system, to the base of the Coal 1 seam (Fig. 8). A change in the stacking pattern at the base and the occurrence of an incised-valley system at the top define this sequence (Fig. 9a, b, c).

Sequence 5 extends from the base of the Coal 1 seam to the base of Coal 3 (Fig. 8) and is also defined by another incised-valley system overlying sequence 4 as illustrated in two sections shown in Figure 9a, b.

Sequence 6 contains all strata in the topmost incised-valley system at the base of Coal 2 and is bounded at the top (Fig. 8, SB II in Fig. 17) by the Mannville-Colorado Group second-order sequence boundary (Banerjee et al., 1994).

Four regional coal seams – LMR, UMR, Coal 1, and Coal 2 – overlie third-order sequence boundaries (Fig. 8) which coincide with transgressive surfaces. These coal seams also locally drape over incised-valleys and elsewhere lie flat on interfluvial areas above what has been called an interfluvial sequence boundary (IFSB) (Aitken and Flint, 1994).

SEQUENCE STRATIGRAPHY OF COAL SEAMS

Previous work

In the last two decades, a number of studies have contributed to the basic principles of coal seam sequence stratigraphy. A few worldwide generalizations can be made from these studies.

First, most regionally extensive coal seams lie on, or close to the maximum flooding surface of major (second-order?) depositional sequences (Lawrence, 1982; Ryer, 1984; Cross,

1988). Hamilton and Tadros (1994) came to the same conclusion but called the maximum flooding surface a "genetic stratigraphic sequence boundary", applying the Galloway (1989) model to coal stratigraphy, and considered regional coal seams to overlie such sequence boundaries.

Secondly, although coal seams may occur both in the transgressive and the early highstand parts of a sequence, most widespread coals form by ponding along coastal plains initiated by the transgressive cycle (Arditto, 1991). Bases of coal seams in most cases represent transgressive surfaces which commonly coincide with sequence boundaries (Aitken, 1995; Aitken and Flint, 1995). Ravinement surfaces may directly overlie coal seams followed by a marine condensed section (Gastaldo et al., 1993).

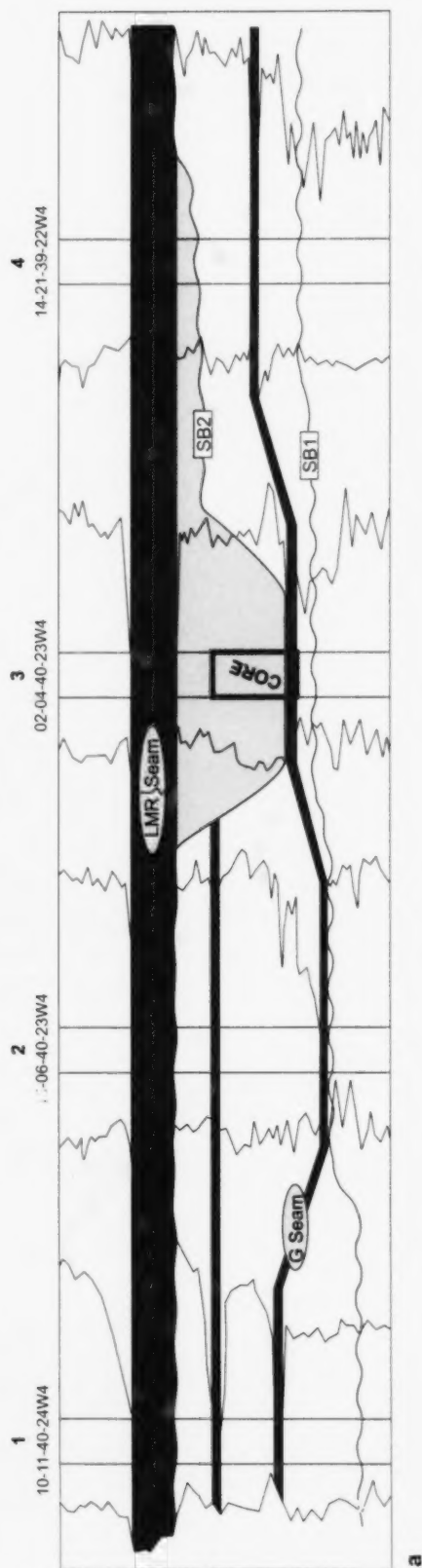
Next, coals drape over incised-valley-fills and overlie interfluvial sequence boundaries (Aitken and Flint, 1994; Read, 1995).

And finally, in a prograding situation, imbricate stacks of parasequences (fourth-order sequences), may each be draped by minor coal seams that coalesce landward to form thicker, more extensive regional seams (Herbert, 1997) at sequence boundaries (of the Exxon model).

Sequence stratigraphy of Mannville coals

In the Mannville situation, all of the above generalizations apply. For example, the thickest and most extensive coal seam (LMR) lies close to the maximum flooding surface (Fig. 8) and all coal development in the second-order Mannville sequence is confined to the HST (Fig. 17). Next, regional coal seams lie over third-order sequence boundaries where the TS and SB generally coincide. Also, regional coal seams drape over incised-valley-fills and overlie interfluvial sequence boundaries (Fig. 9a, b, c). Lastly, the fourth-order sequences (Banerjee et al., 1996) recognized in the Mannville Group, are stacked as progradational wedges delineated by coal seam splits (see discussion below).

Figure 14. Detailed core photographs of coal-bearing strata in well 6-6-38-19W4. Examples of coarsening-upward sequences interpreted as parasequences are shown. The top of the core is at 1276.5 m and the bottom at 1285.9 m. The G seam (marked G), lies over a rooted, structureless siltstone representing an underclay (uc) or paleosol. The base of the G seam is a fourth-order sequence boundary (sb) coinciding with a flooding surface (fs), which probably is a fourth-order transgressive surface. A flooding surface (fs) on top of the G seam terminates the parasequence. The rest of the core coarsens upward toward the right of the photograph until it is terminated by another flooding surface (fs) at the extreme right-hand column marking the contact with strata that contain a fourth-order sequence boundary (sb) below a thin coal seam (c) and one terminated by a third flooding surface. Flooding of both seams with burrowed, marine-influenced sediments indicates their transgressive origin (GSC photo no. 4609-22-25). The core is continuous from bottom left corner to the top right corner of the page.



2-4-40-23W4

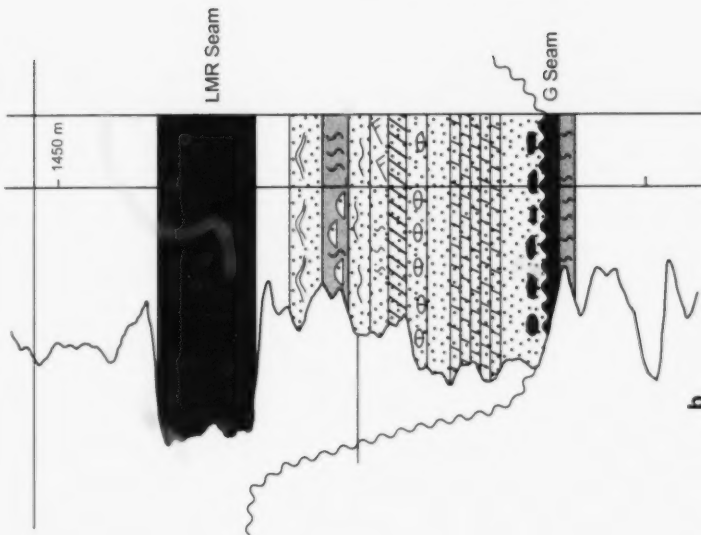
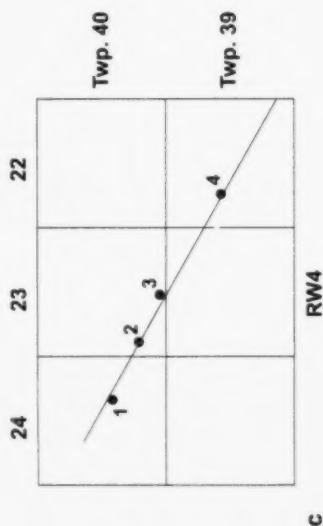


Figure 15. Lithology log of incised-valley-fill deposits. Examples from cored intervals in Sequence 2. **a.** Stratigraphic cross-section based on lithological and gamma-ray density logs of an incised valley at a sequence boundary showing the location of the cored interval of the valley-fill deposits. **b.** Lithology of the valley-fill in well 2-4-40-23W4. Note: 1) lining-upward trend in the deposits; 2) erosional base with a layer of coal clasts and high-angle cross-stratification in the bottom half of the deposit; and 3) rare burrowing toward the top of the valley-fill. Burrowing and flaser bedding indicate marine connection and tidal influence. **c.** Location of wells.

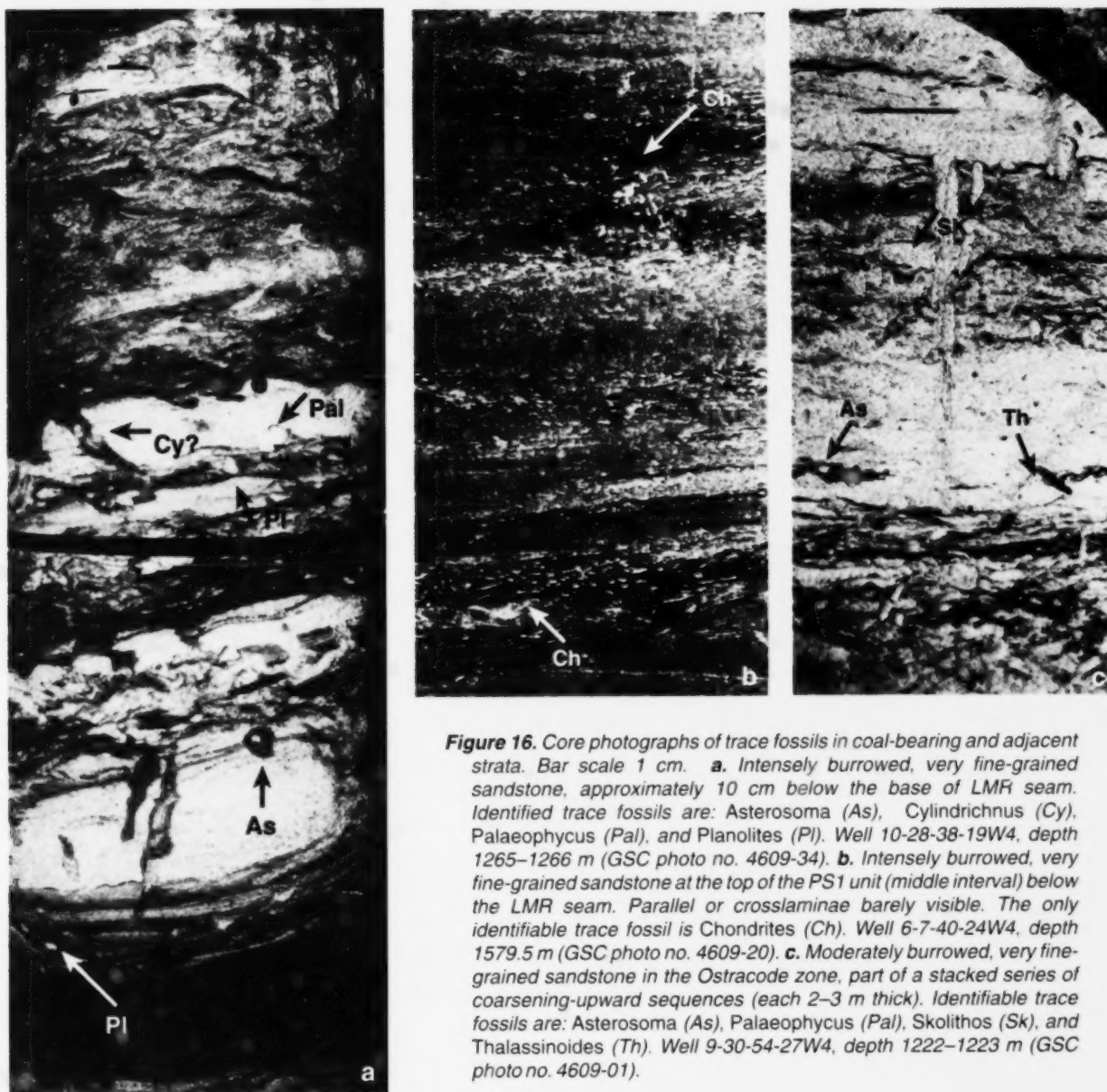
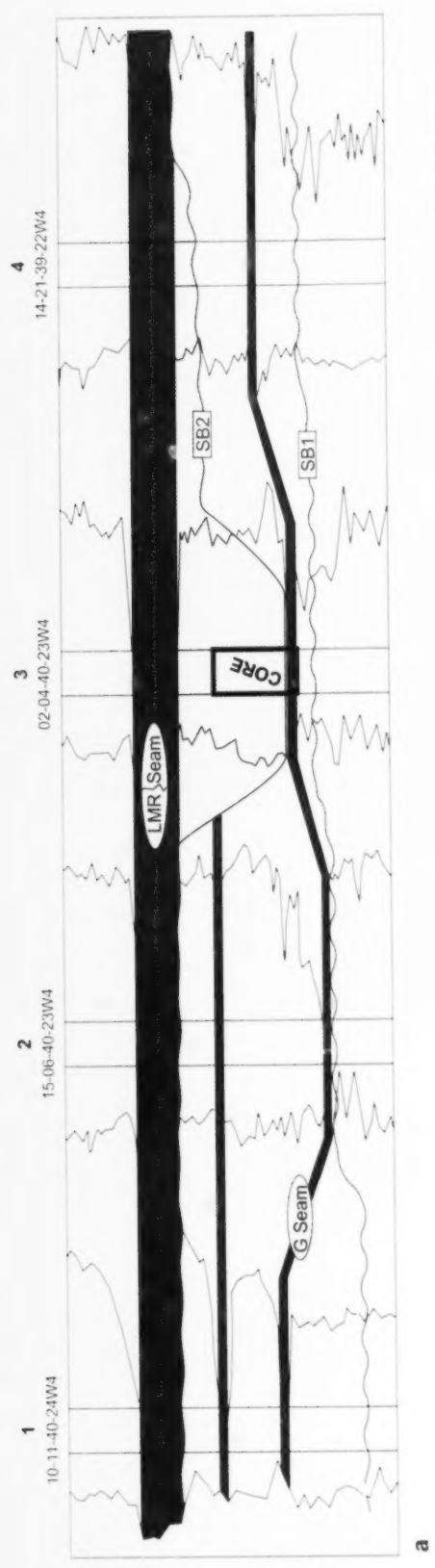


Figure 16. Core photographs of trace fossils in coal-bearing and adjacent strata. Bar scale 1 cm. **a.** Intensely burrowed, very fine-grained sandstone, approximately 10 cm below the base of LMR seam. Identified trace fossils are: *Asterosoma* (As), *Cylindrichnus* (Cy), *Palaeophycus* (Pal), and *Planolites* (Pl). Well 10-28-38-19W4, depth 1265–1266 m (GSC photo no. 4609-34). **b.** Intensely burrowed, very fine-grained sandstone at the top of the PS1 unit (middle interval) below the LMR seam. Parallel or crosslaminae barely visible. The only identifiable trace fossil is *Chondrites* (Ch). Well 6-7-40-24W4, depth 1579.5 m (GSC photo no. 4609-20). **c.** Moderately burrowed, very fine-grained sandstone in the Ostracode zone, part of a stacked series of coarsening-upward sequences (each 2–3 m thick). Identifiable trace fossils are: *Asterosoma* (As), *Palaeophycus* (Pal), *Skolithos* (Sk), and *Thalassinoides* (Th). Well 9-30-54-27W4, depth 1222–1223 m (GSC photo no. 4609-01).

Pattern of coal seam splits: the fourth-order sequences

As shown in the summary cross-sections of the regional stratigraphy in Figure 3, all major coal seams in the Mannville Group and particularly the LMR seam, show a basinward (NW) progressive splitting pattern that has been recognized in other coal basins (Fielding, 1987; Flint et al., 1995) and Tertiary lignite deposits (Coates et al., 1980).

Patterns of amalgamation and merging of the Mannville coal seams (Fig. 9) have been schematically presented in Figures 3 and 17 to illustrate the basic sequence stratigraphic hierarchical orders. According to this hierarchical arrangement, the whole coal-bearing succession of the Upper Mannville subgroup belongs to the HST of the second-order Mannville sequence (Fig. 17). It is also apparent that the third-order sequences within the subgroup have an aggradational stacking pattern (Fig. 8).



2-4-40-23W4

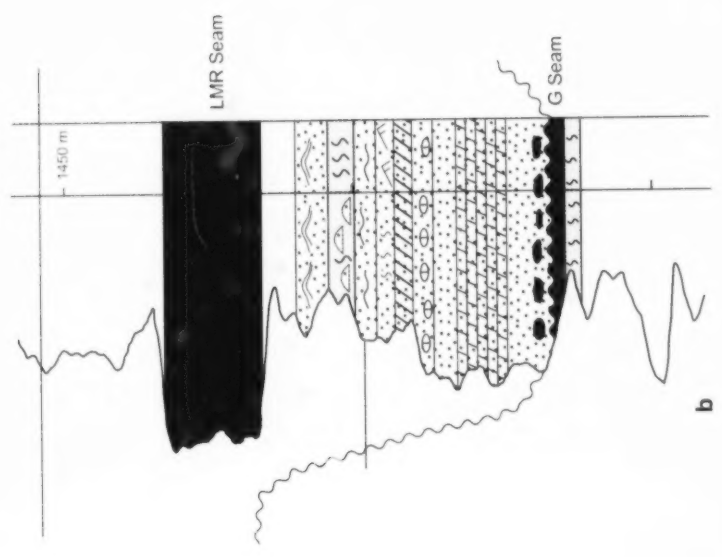
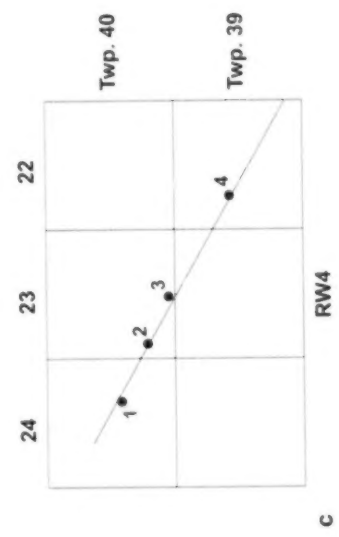


Figure 15. Lithology log of incised-valley-fill deposits. Examples from cored intervals in Sequence 2. **a.** Stratigraphic cross-section based on lithological and gamma-ray density logs of an incised valley at a sequence boundary showing the location of the cored interval of the valley-fill deposits. **b.** Lithology of the valley-fill in well 2-4-40-23W4. Note: 1) fining-upward trend in the deposits; 2) erosional base with a layer of coal clasts and high-angle cross-stratification in the bottom half of the deposit; and 3) rare burrowing toward the top of the valley-fill. Burrowing and flaser bedding indicate marine connection and tidal influence. **c.** Location of wells.

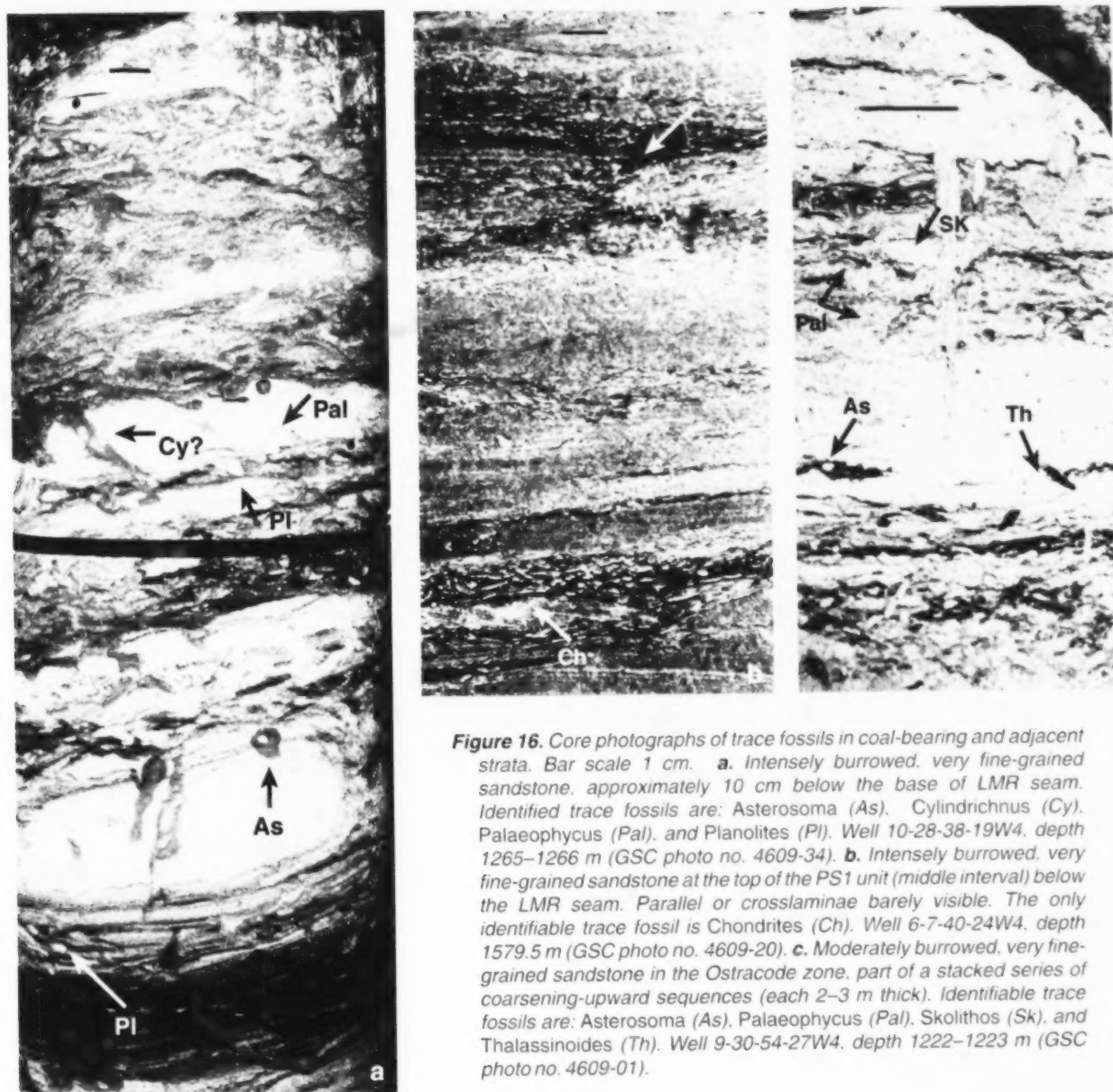


Figure 16. Core photographs of trace fossils in coal-bearing and adjacent strata. Bar scale 1 cm. **a.** Intensely burrowed, very fine-grained sandstone, approximately 10 cm below the base of LMR seam. Identified trace fossils are: *Asterosoma* (As), *Cylindrichnus* (Cy), *Palaeophycus* (Pal), and *Planolites* (Pl). Well 10-28-38-19W4, depth 1265–1266 m (GSC photo no. 4609-34). **b.** Intensely burrowed, very fine-grained sandstone at the top of the PS1 unit (middle interval) below the LMR seam. Parallel or crosslaminae barely visible. The only identifiable trace fossil is *Chondrites* (Ch). Well 6-7-40-24W4, depth 1579.5 m (GSC photo no. 4609-20). **c.** Moderately burrowed, very fine-grained sandstone in the Ostracode zone, part of a stacked series of coarsening-upward sequences (each 2–3 m thick). Identifiable trace fossils are: *Asterosoma* (As), *Palaeophycus* (Pal), *Skolithos* (Sk), and *Thalassinoides* (Th). Well 9-30-54-27W4, depth 1222–1223 m (GSC photo no. 4609-01).

Pattern of coal seam splits: the fourth-order sequences

As shown in the summary cross-sections of the regional stratigraphy in Figure 3, all major coal seams in the Mannville Group and particularly the LMR seam, show a basinward (NW) progressive splitting pattern that has been recognized in other coal basins (Fielding, 1987; Flint et al., 1995) and Tertiary lignite deposits (Coates et al., 1980).

Patterns of amalgamation and merging of the Mannville coal seams (Fig. 9) have been schematically presented in Figures 3 and 17 to illustrate the basic sequence stratigraphic hierarchical orders. According to this hierarchical arrangement, the whole coal-bearing succession of the Upper Mannville subgroup belongs to the HST of the second-order Mannville sequence (Fig. 17). It is also apparent that the third-order sequences within the subgroup have an aggradational stacking pattern (Fig. 8).

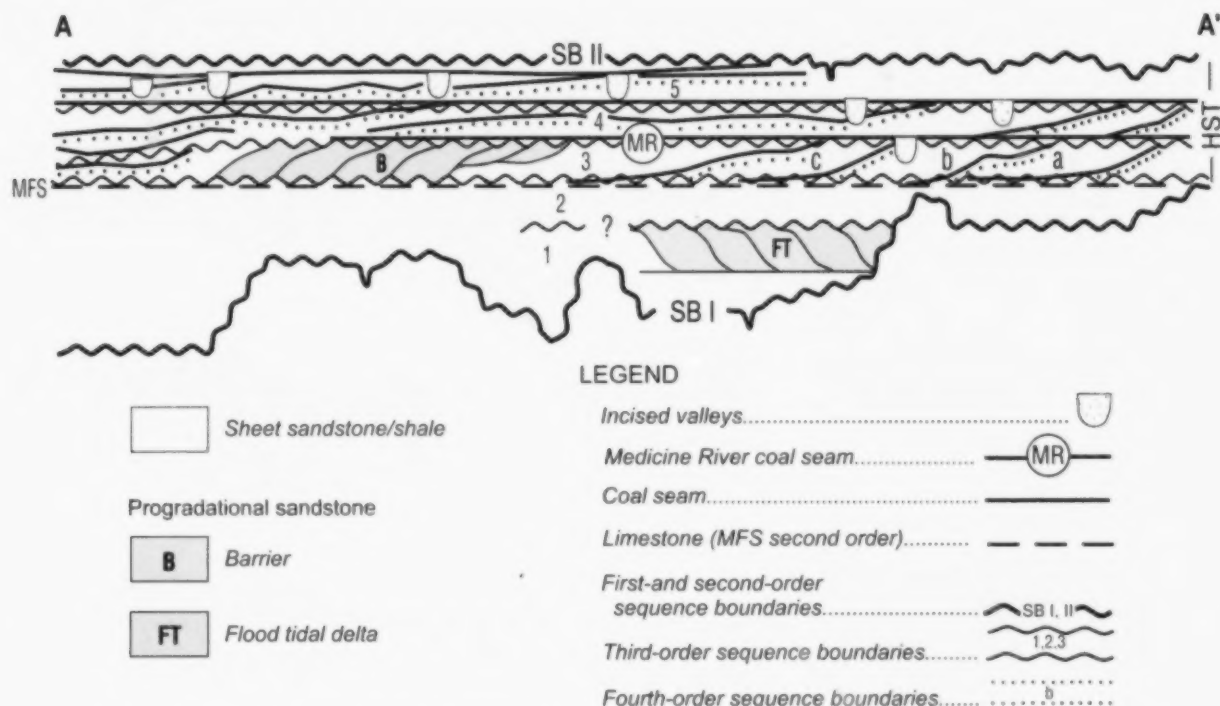


Figure 17. A sequence stratigraphic interpretation of the cross-section of lines 1, 2 and 3 in Figure 3, showing the hierarchy of sequences within the Mannville Group. SB I is a first-order sequence boundary and SB II a second-order one. Coal seam splits define fourth-order sequences (see Fig. 21) marked a, b, c. These are arranged within subhorizontal third-order sequences as stacked progradational wedges. Most coal seams overlie third-order sequence boundaries or drape over incised-valley fills. Larger sandstone bodies have been interpreted in terms of barrier islands, flood tidal deltas, and incised-valley fills.

The coal seam splits (located at a, b, and c in Fig. 17) lying between these parallel third-order sequence boundaries define progradational wedges within individual third-order sequences. These progradational wedges have been defined as high-frequency sequences (fourth-order) produced by single transgressive-regressive cycles (Banerjee et al., 1996).

Coal seam splits and TR cycles

For peat accumulation and preservation to occur, the availability of plant materials and the height of the groundwater table are the two most important parameters. Above the water table, peat accumulation is inhibited by oxidation and erosion, and if the rise of water table exceeds plant growth, drowning of the mire terminates peat accumulation. Thus, the water table is the base level of deposition for peat.

In coastal environments, where most coals are formed, the water table generally coincides with, and is thus

influenced by, sea level. On the basis of this simple relation, Diessel (1992, p. 472, Fig. 8.4 A-E; Fig. 18) presented a model in which a transgressive-regressive coal-seam couplet separated by a wedge of marine sediment would form in a single base-level cycle. This couplet can be used as a building block for sequence stratigraphy of coal (Fig. 17).

Coal-seam splits can form in various ways, including contemporaneous channel sedimentation (Elliot, 1969), compaction-controlled subsidence (Fielding, 1986), basinward increase in subsidence (Fielding, 1987), and landward amalgamation of flooding surfaces (Flint et al., 1995). In order to prove that the split has formed because of sea-level fluctuations, it must be established that the upper seam is regressive, the lower seam is transgressive, and that the split consists of marine sediments. The first and second criteria can be inferred from the geochemical, organic petrological, and palynological signatures of the coal seams, and the third can be demonstrated by paleontological and sedimentological data from the split.

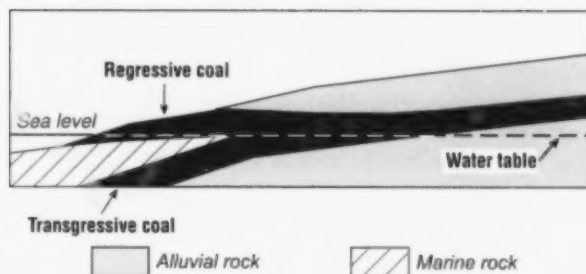


Figure 18. A coal seam split produced in a single transgressive-regressive (TR) cycle as envisaged in a model by Diessel (1992). In ideal conditions, the transgressive coal would overlie continental sedimentary strata and be overlain by the marine strata of the split. The regressive coal must also be overlain by alluvial strata. The transgressive and regressive coal seams forming the lower and upper leaves of the split seam should also exhibit characteristic signatures in their coal character profiles. This TR couplet model has been used to interpret the coal-seam splits studied here.

GEOCHEMICAL AND PETROLOGICAL SIGNATURES OF COAL SEAMS

Analytical procedures

Petrographic analysis

Petrographic analysis was carried out on polished core samples using image analysis techniques (Pratt, 1989, 1993; Marchioni et al., 1994). The samples were cut to approximately 5 to 7 cm lengths and prepared for petrographic analysis using standardized procedures (Bustin et al., 1985). The first step was to establish a lithotype log followed by image analysis along a vertical traverse path. Consecutive columnar samples of the seam were analyzed along a predefined traverse section, providing information on changes in petrographic seam characteristics from base to top. The increments used to describe vertical changes were 0.5 mm in height, thus yielding information at a very high level of resolution. Results reported here are based on the average composition of four images at each of these increments, representing a 1.65 mm wide band.

Since image analysis discriminates the coal macerals at the group level, additional conventional point counting was carried out at the maceral level to define maceral ratios, such as the gelification and tissue preservation indices. Traditional maceral analysis also was carried out on samples from well 6-7-40-24W4, which were characterized by high amounts of detrital components for which a discrimination

by image analysis was not possible. The nomenclature used for identifying the various macerals is that of the ICCP (1963, 1994).

In-seam vitrinite reflectance variations were obtained by image analysis techniques using the reflectogram distributions from those samples analyzed for petrographic compositions, whereas the samples from well 6-70-40-24W4 were analyzed using standard analytical methods (Bustin et al., 1985).

Sulphur determination

Total sulphur was determined on an "as received" basis using a LECO SC-32 Sulphur Determinator. The instrument was calibrated using a 0.82 $\pm$ 0.04 sulphur coal standard. Operating temperature was 1500°C with a minimum acquisition time of 120 seconds. The samples were run in duplicates and the average of the two values is reported here.

Rock-Eval

Rock-Eval/TOC analysis of coal samples corresponding to intervals analyzed by petrographic methods were carried out using a Delsi Rock-Eval II pyrolysis unit equipped with a total organic carbon (TOC) analysis module. The procedure is that outlined by Fowler et al. (1991).

TYPICAL SIGNATURES OF COAL SEAMS

Typical signatures of transgressive and regressive coal seams (Fig. 19a), were originally formulated by Diessel (1992) from a large database of the Paleozoic coals of Germany and Australia. These signatures have been modified slightly in this study, based on the following coal characters: hydrogen content, sulfur content, vitrinite reflectance, maceral associations and resulting tissue preservation index (TPI), gelification index (GI) and vitrinite/inertinite ratio.

Hydrogen and sulfur contents tend to be higher in seam sections close to the seam tops when overlain by marine strata (Fig. 19a). This is commonly reflected in changes in maceral composition, typically an enrichment in lipid-rich degraded components. Vitrinite reflectance and maceral fluorescence intensity are likewise influenced by proximity to marine strata (Fig. 19a). The upward increase in anaerobic bacterial activity in the precursor mires (Diessel, 1992) influences the type of vitrinite and inertinite macerals. The TPI values define the ratio of macerals showing remnant botanical cell structure over those components with no such structure. The TPI values indicate at the same time

predominant precursor materials and the degree of degradation of the organic matter. The GI values define the ratio of macerals that underwent gelification over those which did not and are generally considered to indicate the wetness of the precursor mire. The vitrinite/inertinite ratio (V/I) also indicates the degree of wetness within the precursor mire.

In transgressive seams, the vertical profile (Fig. 19a) of these petrographic characters is a reflection of a rising water table and ultimate drowning of the mire by the advancing sea. In a regressive seam, the profile displays the reverse trend manifested by a falling water table and ultimate subaerial exposure of the peat.

Summary of palynology of coal seams

In vegetated coastal lowlands, plant communities display a parallel zonation, with decreasing marine influence from the shoreline landward (Casagrande et al., 1974; Coates et al., 1980; Diessel, 1992). In a transgressive coal seam, this results in a particular vertical zonation in the palynomorph assemblages (Schneider, 1984); the reverse zonation would

represent a regressive seam. In a typical back barrier situation such as the Brataria basin of the Mississippi Delta, Kosters et al. (1987) described such a zonation of peat-forming environments which, based on palynological data, varied successively landward from saline, to brackish, intermediate, freshwater marsh, and finally to a forested wetland or swamp.

In the Lower Cretaceous (Mannville) coal seams of the WCSB, the palynological analysis led to the recognition of five plant communities (Fig. 20, Table 1). This was done on the basis of terrigenous pollens and spores and aquatic cysts, including dinoflagellates (Banerjee et al., 1995, 1996). In a transgressive seam, the vertical succession of palynomorphs shows increasing marine influence and decreasing tree cover, from forested swamps at the base to salt marsh at the top (Fig. 19b). In a regressive seam a reverse trend is found (Fig. 19b).

The Twin Coal depositional model

Regionally extensive paralic coal seams tend to split successively in a basinward direction, as has been observed

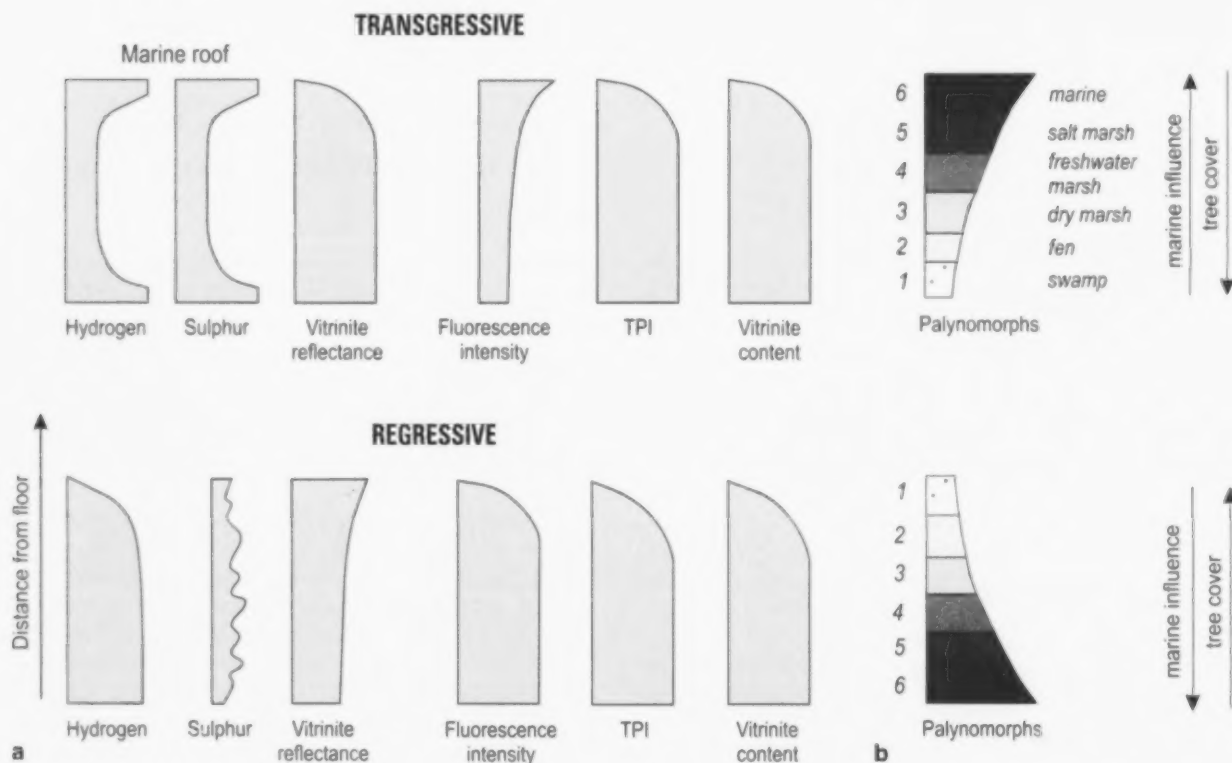


Figure 19. Ideal signatures in coal character profiles for transgressive and regressive seams. See text for explanation.
a. Geochemical and organic petrological characters. **b.** Palynological successions.

6	Marine	Shale	
5	<i>Polypodium</i>	Salt marsh	
4	<i>Zygnema</i>	Freshwater marsh	
3	<i>Gleichenia</i>	Dry marsh	
2	<i>Taxodium/Gleichenia</i>	Fen	
1	<i>Taxodium</i>	Swamp	

Figure 20. Succession of palynoflora in a typical Lower Cretaceous Mannville Group transgressive seam indicating decreasing influence of tree cover and increasing influence of salinity toward the roof of the seam (also see Table 1). A regressive seam would show a reverse palynofloral succession.

in the Westphalian of England (Fielding, 1987). A similar splitting pattern in the Cretaceous coals of Utah has been interpreted as landward merging of several flooding surfaces into one, so that a number of parasequences are amalgamated (Flint et al., 1995). On the basis of studies of coal-bearing Upper Mannville strata in the WCSB, we presented a new model for coal-seam splits, the Twin Coal depositional model (Banerjee et al., 1996). In this model, boundaries between successive splits have been interpreted as higher order (fourth) sequence boundaries.

Successive TR coal couplets can be stacked laterally in a prograding pattern (Fig. 21) if sea level falls below the lower leaf of the split seam before deposition of the next couplet. This will expose the clastic wedge within the TR coal couplet to subaerial erosion, producing an unconformity. Each TR coal couplet will, therefore, be bounded by an unconformity below the transgressive coal and one above the regressive coal. A series of these high-frequency (fourth- or higher order) unconformity-bounded sequences (Fig. 21) stacked in a progradational pattern would form a lower order sequence (third or lower). A similar model of thick accumulation of peat above a prograding platform behind a barrier, has been proposed by Galloway and Hobday (1996, p. 342) based on a case study in the Mississippi Delta by Koster and Suter (1993).

According to our model, at the start of each base-level cycle, the sea rises from the lowest level (Fig. 22a), and peat accumulation takes place just landward of the shoreline. As sea level continue to rise (Fig. 22b), seawater drowns the peat, and a wedge of marine sediments is deposited on the peat layer. Ultimately, sea level rises to maximum flooding level, at which time it may become stable for a period (stillstand). The shoreline sediments might start prograding seaward on top of the maximum flooding surface overlying the wedge of sediments forming the transgressive systems tract. The regressive seam starts forming at this point on top of the prograding platform (Fig. 22c). To start the next cycle (the next seaward split as in Fig. 21), the sea must fall to its lowest level, exposing the depositional surface to subaerial erosion, forming an unconformity (Fig. 22d). The next cycle

Table 1
Significant characteristics of the palynocommunities of the Mannville Group coal seams

Plant (facies) community	Main algal	Main pollen	Main spores	Comments
Marginal-marine (shale)	rare ceratoid dinoflagellates plus rare to common <i>Zygnema</i> cysts	<i>Cedrus</i> and <i>Taxodium</i> mixture of upland and marsh pollen	Assorted spores, especially the upland forest types, e.g. schizaeaceous ferns	high diversity
<i>Polypodium</i> brackish marsh	rare <i>Breodoxella</i> plus common <i>Zygnema</i> cysts	<i>Taxodium</i> and <i>Cedrus</i>	<i>Polypodium</i> plus <i>Gleichenia</i>	low- to moderate-diversity
<i>Zygnema/Gleichenia</i> freshwater marsh	common to abundant <i>Zygnema</i> cysts	<i>Taxodium</i> secondary	<i>Gleichenia</i> dominant with <i>Polypodium</i> often secondary	moderate diversity
<i>Zygnema/Gleichenia</i> freshwater marsh with ponding	Rare to common euryhaline dinoflagellates, i.e. <i>Holmwoodinium</i> and rare <i>Zygnema</i>	<i>Taxodium</i> with a mixture of upland pollen	<i>Gleichenia</i> dominant <i>Distaltriangulisporites</i> common	occasionally rare angiosperm pollen; high diversity
<i>Gleichenia</i> dry marsh or raised bog	rare to absent <i>Zygnema</i> cysts	<i>Taxodium</i> co-dominant	<i>Gleichenia</i> co-dominant occasionally common lygodiacean spores	low diversity
<i>Taxodium/Gleichenia</i> fen	rare to absent <i>Zygnema</i> cysts	<i>Taxodium</i> dominant	<i>Gleichenia</i> secondary	moderate diversity
<i>Taxodium</i> swamp	absent	<i>Taxodium</i> dominant	<i>Gleichenia</i> rare along with other ferns	low diversity
<i>Taxodium</i> swamp with ponding	Rare to common euryhaline dinoflagellates, i.e. <i>Holmwoodinium</i>	<i>Taxodium</i> dominant <i>Cedrus</i> rare	<i>Gleichenia</i> rare along with other ferns common	moderate diversity
<i>Taxodium/Cedrus</i> forest bog	absent	<i>Cedrus</i> and <i>Taxodium</i>	common <i>Sphagnum</i> , Anemiacean ferns	low diversity; low palynomorph recovery

starts when sea level begins to rise again and peat accumulation takes place landward of it (Fig. 22e). Thus, in each of the base-level cycles a fourth-order sequence is formed. As seen in Figure 22b-e, all fourth-order sequence boundaries merge landward into a composite unconformity surface that becomes a third-order sequence boundary contained within the regionally thick seam (Fig. 21).

The model as presented above is based on two assumptions: first, that the TR couplet, as shown in Figure 18, is fully developed, and second, that all the components of the Exxon model are represented in the stratal succession within these high-frequency sequences. However, the model would depart from the ideal situation when the regressive part of the TR couplet is not preserved. Consequently, an amalgamated seam may represent only stacked transgressive coals separated by high-frequency sequence boundaries without the regressive counterparts. Also, the elaborate stratal patterns within the fourth-order sequences shown in Figure 22 may not develop and only a subtle onlapping relation and the presence of a thin coal seam at the maximum flooding surface, would reveal their nature (see Fig. 23).

The above observations are significant in solving the enigma of thick (>5 m) paralic coal seams. Thick seams could form by amalgamation of a number of high-frequency sequences (Fig. 21) and should normally contain a number of unconformities (sequence boundaries) as envisaged by Shearer et al. (1994).

DETAILED STUDY OF THE MEDICINE RIVER AND THE G SEAMS

Within the broad framework of the sequence stratigraphy of the Upper Mannville strata, a detailed analysis of the stratigraphy, sedimentology, palynology, organic petrology, and geochemistry of the Upper Medicine River (UMR), Lower Medicine River (LMR), and G coal seams is presented in this section.

Coal seam stratigraphy

Three coal seams, the two Medicine River seams (LMR and UMR) and the G seam were chosen as the subjects of this study. As shown in Figure 24a, the Medicine River seams show a step-like splitting pattern between locations X (well 07-01-21-37W4) and Y (lying between wells 10-25-40-25W4 and 06-07-40-24W4; see Fig. 25). The G seam, which is approximately 0.5 m thick here (Strobl, 1988; Rosenthal, 1988), represents the lowermost coal zone to appear in the Upper Mannville stratigraphic succession above the Glauconitic Sandstone. This seam, which at places consists of a number of thin seams or a coal zone, is not continuous but occur at approximately the same stratigraphic level. In this study, the G seam or seams have been interpreted as a group of successive splits of the LMR seam as shown in Figure 24b. According to this interpretation, they are lithostratigraphically equivalent but diachronous in nature.

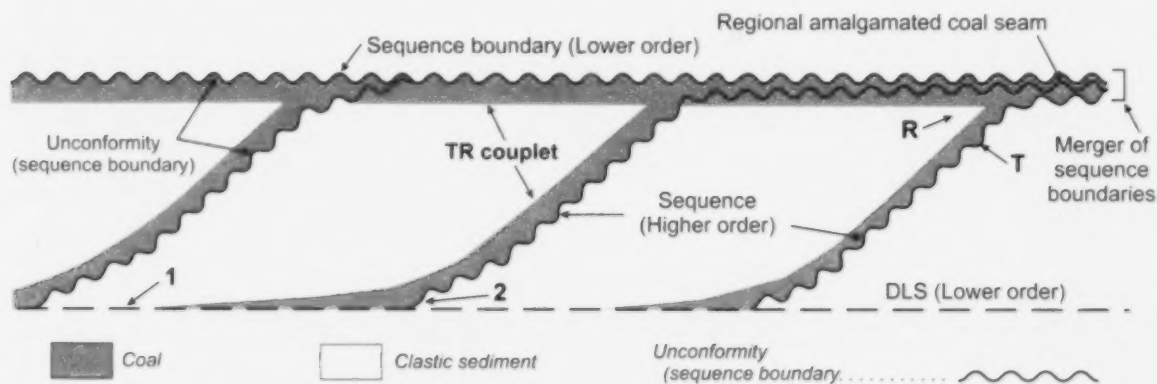
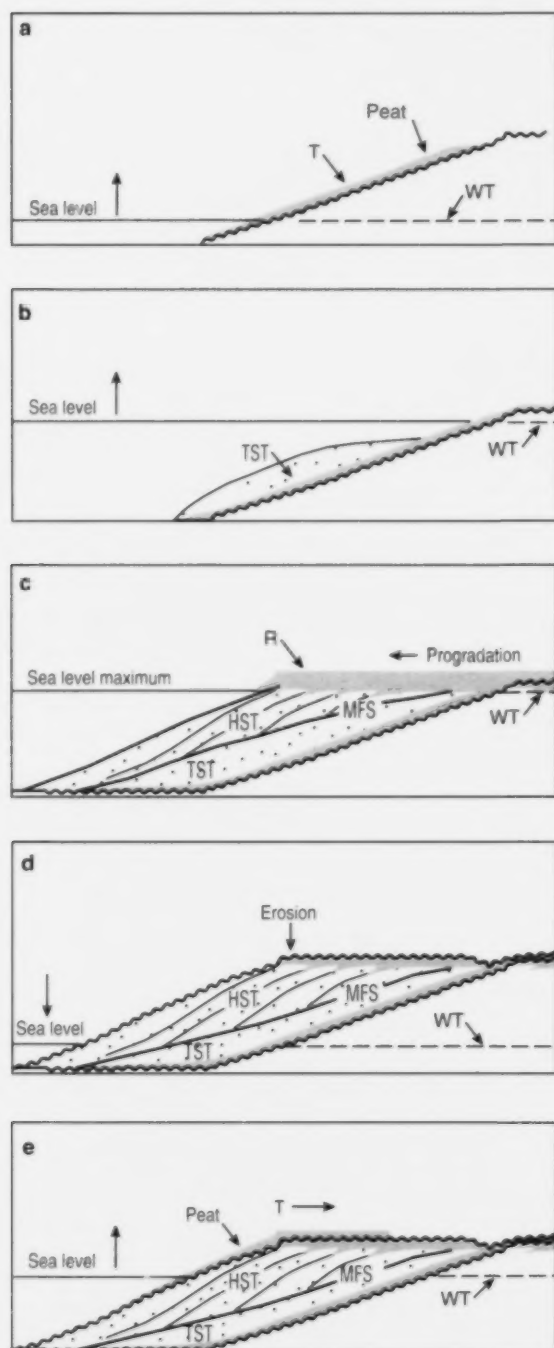


Figure 21. A conceptual model illustrating the relationship between TR coal couplets, merging of the higher order sequence boundaries into lower order ones, and formation of an amalgamated coal seam on a progradational platform over a series of stacked progradational wedges of higher order sequences. T and R coal seams of the higher order sequences would exhibit simple T or R signatures, but the amalgamated seam at the right of the diagram would show a complex profile of multiple TR cycles separated by unconformities. The amalgamated seam would overlie a lower order sequence boundary. T - transgressive, R - regressive.

The two Medicine River seams are thicker (>5 m) and regionally more extensive (Dawson and Kalkreuth, 1994; Hughes, 1994) than the seams lying above them. Two regional coal seams (Coal 1 and 3) can be recognized above the Medicine River seams, which overlie sequence boundaries. These seams split, merge, pinch out, and are eroded out in a complex pattern (Fig. 3a, b, c; 9a, b, c).



A schematic interpretation of the apparently random splitting and merging of coal seams is shown in Figure 17, which illustrates amalgamation of fourth-order sequence boundaries into third-order ones. An arrangement of stacked progradational wedges of these fourth-order sequences within horizontal third-order boundaries can explain these amalgamations and splits (Fig. 24a).

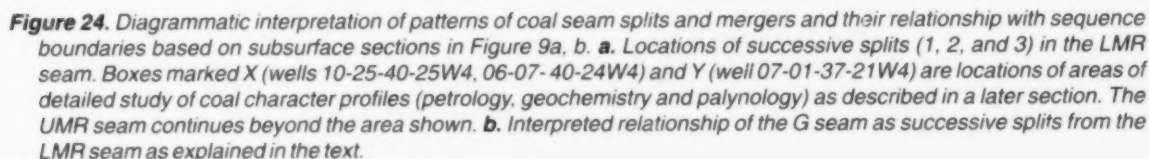
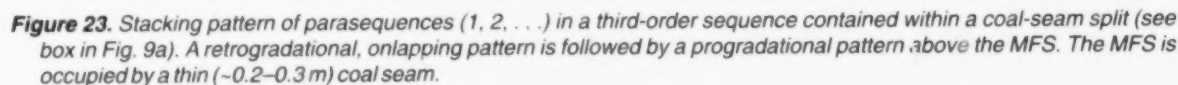
Two locations (X and Y in Fig. 24a) chosen for detailed study illustrate two aspects of the sequence stratigraphy of the coal seams. In location Y, cored intervals of coal from five wells are available for study of the LMR and the G seams. Here, the focus of the study was the patterns of coal seam splitting and the transgressive and regressive nature of the coal seams (Banerjee et al., 1996) as revealed by the seam profiles of geochemical, petrological, and palynological data.

In location X, the focus of the study was the amalgamated LMR-UMR seam in the 07-01-37-21W4 well where a 12 m core, which included one shale parting, were available for study. Here the subject of the study was the complexities within the thick seam, including presence of unconformities and amalgamation of high-frequency sequences. The stratigraphic relations between coal seams in these two locations are illustrated in Figure 24a.

Study of coal seam split (location Y)

The LMR seam at location Y presented an opportunity to study both the upper and lower leaves of the split seam (3 in Fig. 24a) because there were cores available (although partial) of both leaves of the seam. The G seam lying below the LMR seam and above the topmost limestone also seems to be a split off the LMR seam as shown by the correlation in wells 10, 11 and 12 in Figure 25.

Figure 22. The origin of fourth-order sequences through base level cycles. **a.** The beginning of the cycle. The sea level as well as the water table (WT) controlled by it, are both rising. Peat accumulation is taking place ahead of the rising sea just below the water table. **b.** Peat is drowned by the advancing sea. A wedge of transgressive marine sediments forming the transgressive systems tract (TST) buries the peat layer as it moves landward. **c.** Sea level is at its maximum. The maximum flooding surface (MFS) has been formed, over which the land-derived sediments prograde seaward forming the highstand systems tract (HST) overlying the TST. The sea retreats and a regressive peat layer builds seaward over the prograding platform. **d.** Forced regression. The sea level falls and subaerial erosion follows forming an unconformity (fourth-order sequence boundary) over the sediment wedge and the regressive peat layer. **e.** Sea level rises again starting the next cycle.



To prove that the split coal seam at location Y represents a single TR cycle (Fig. 18), it had to be demonstrated that the shale split is marine, and that the lower leaf of the LMR seam is transgressive and the upper leaf regressive. The G seam (another lower split from LMR) should also be shown to be transgressive in nature.

The marine nature of the shale split is demonstrated by the presence of pyritic, organic-rich black shale, pyritized *Skolithos* burrows and the marine dinoflagellate *Balmula* found in the shale parting.

The transgressive nature of the lower leaf of the LMR seam is confirmed by the presence of two marine dinoflagellates in the coal seam, (*Odontochitina* and *Holmwoodinium*). The core through the lower leaf of the seam comes from a well (10-25-40-25W4 in Fig. 13, 25) where only the lowermost 1 m of the lower leaf has been cored. The palynological profile of the seam shows an oscillating to overall transgressive floral succession. But the petrological/geochemical profile is more complex.

Petrography of the LMR seam, lower leaf

Results from manual point-counting of macerals and minerals from the seam are summarized in Table 2. The data were determined on the basis of lithotype variations within the seam; in other words, the maceral composition was determined for each identified lithotype. The dull and dull-banded lithotypes are dominated by semifusinite, fusinite, and inertodetrinite (Table 2), whereas the brighter lithotypes (bright, banded bright) have in general a higher content of vitrinite. Mineral matter consists of quartz, clay minerals, some carbonate, and pyrite. The latter occurs in high concentrations at the base of the seam (Table 2).

The lithotype-log obtained from automated image analysis (Fig. 26A) indicates numerous changes in the brightness of the coal, including a number of pronounced dulling- and brightening-upward sequences. The changes in the brightness of the coal are related to changes in overall petrographic composition (Fig. 26A), with dull lithotypes indicating a larger input of mineral matter (Dm) and/or inertinite (Di). In the brighter lithotypes (BB, B), inertinite and mineral matter are much less abundant and vitrinite is typically the dominant maceral (Fig. 26B). During accumulation of the peat five major flooding events occurred, which resulted in a significant influx of mineral matter (Fig. 26B). In contrast, dull lithotypes (Di) associated with large concentrations of disintegrated inertinite but low mineral matter contents (Fig. 26A) are associated with peat that formed near or above the water table precluding major flooding (Marchioni and Kalkreuth, 1991). The brighter lithotypes are indicative of peat accumulations in wet to moderately wet forest moors. The vitrinite/inertinite ratio (Fig. 26C) is used as a relative measure of the height of the

water table during peat accumulation. The ratio is highly variable throughout the seam and in places indicates abrupt changes from wet to drier conditions and vice versa. The top of the seam interval is characterized by an initial low ratio above the parting (Fig. 26C), before the establishment of much wetter conditions right at the top. The base of the seam shows initially overall wet conditions (Fig. 26C), before a marked shift toward to drier conditions.

Tissue preservation and gelification indices were calculated from the maceral data and are shown in Table 2. They essentially reflect the variations in petrographic composition of the lithotypes, without showing any definitive trend in terms of changes along the vertical seam profile.

Geochemistry of the LMR seam, lower leaf

The total sulphur distribution within the LMR seam (lower leaf) is shown in Figure 26D. The values range from 0.13 to 3.45 wt. %. The lowest sulphur values were recorded for those seam intervals rich in mineral matter, suggesting a predominantly organic affinity for the sulphur. The high sulphur value at the base of the seam may indicate brackish water conditions during peat accumulation.

Hydrogen indices derived from Rock-Eval pyrolysis are highly variable (114 to 297 mg hydrocarbons/g TOC), with the highest values recorded for the base of the seam (Fig. 26E).

Although sequence stratigraphic analysis suggests that the seam is transgressive, geochemical and organic petrological parameters are not conclusive. However, it should be noted that the top 2 m of the seam was not available for analysis. Evidence for the transgressive nature of the seam comes from an overlying organic-rich shale with pyritized *Skolithos* burrows and restricted-marine dinoflagellates (*Pseudoceratium*), and the high sulphur (3.45%) value at the base of the seam.

Palynology of the LMR seam, lower leaf

In the 10-25-40-25W4 well, the palynofloral succession (Fig. 26F) shows the unmistakable transgressive signature of the seam, supporting the conclusions drawn from the stratigraphic and sedimentological studies.

The lower leaf of the LMR seam in the 06-07-40-24W4 well has been analyzed for palynology from broken core samples; no vertical columnar samples could be obtained for petrology and geochemistry. A weak transgressive trend is probably exhibited by a change from a *Gleichenia* dry marsh at the base (1567.6 m) to a *Gleichenia/Polypodium* marsh at the top (1567.1m) (Davies, 1995, pers. comm.).

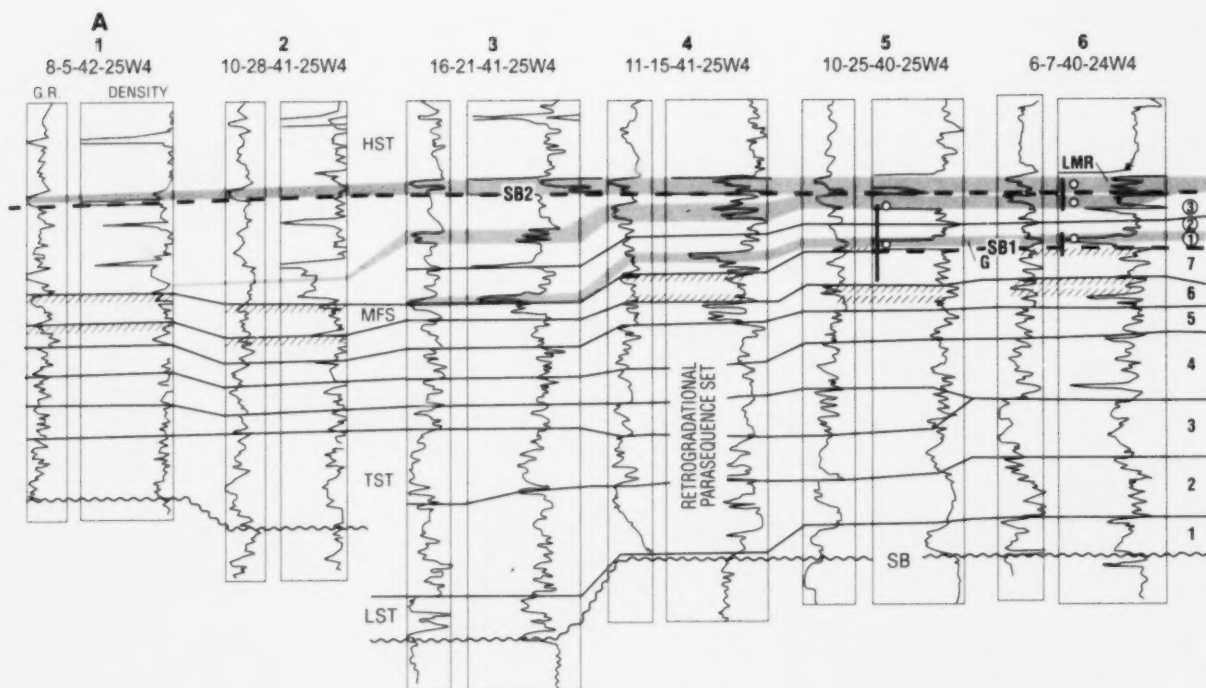


Figure 25. Stratigraphic cross-section based on gamma-ray density log (close to the line X-X' in Fig. 6) showing detailed study of coal seam splits in the Lower Medicine River coal seam (LMR). Note retrogradational stacking pattern below the limestone beds, successive onlaps of parasequences 4, 5, 6, 7 between wells 9 and 10. Locations of the cored intervals sampled for coal character profiles (geochemistry, organic petrology and palynology) and the section line AB (inset) are also shown on an isopach map of the Mannville Group. Note the correlation of parasequences (1, 2, 3...) of Sequence 2 (the middle interval).

Petrography of the LMR seam, upper leaf

The regressive nature of the upper leaf of the LMR seam is suggested by the only available core of this part of the seam, from the 06-07-40-24W4 well (Fig. 25, well 6). From this well, 13 spot samples were collected to study the in-seam variations from the base to the top of the seam. Petrographic analysis showed that many samples are extremely rich in detrital components (inert- and vitrodetrinite), which could not be discriminated optically by image analysis. Petrographic data for this set of samples are instead based on routine manual maceral analysis (point counting) and the results are shown in Table 3.

The data show that except for the sample at the very base of the seam interval (Table 3), all samples have relatively low vitrinite contents (< 50 Vol%). Within the vitrinite and inertinite groups detrital components such as vitrodetrinite and inertodetrinite are predominant in many samples. Liptinite contents are low to moderate (maximum of 15 Vol%), with sporinite most abundant (Table 3). Within

the inorganic fraction clay minerals and quartz are predominant (Table 3).

The interpretation of the regressive nature of the seam is supported by a number of coal petrographic parameters (Fig. 27):

1. The vitrinite contents show a general decrease toward the top of the seam, while inertinite contents increase, as indicated by the plot of vitrinite over inertinite.
2. The upper portion is characterized by the predominance of detrital macerals (inertodetrinite and vitrodetrinite). In some samples, the detrital components make up to 80 percent of the volume of the total organic matter suggesting a severe degradation of the plant material.
3. As a consequence of the second point, tissue preservation indices (TPI) are extremely low (0.01–0.20) except at the very base of the investigated seam interval.
4. Gelification indices (GI) also decrease toward the top of the seam, suggesting that this part of the seam accumulated under drier conditions.

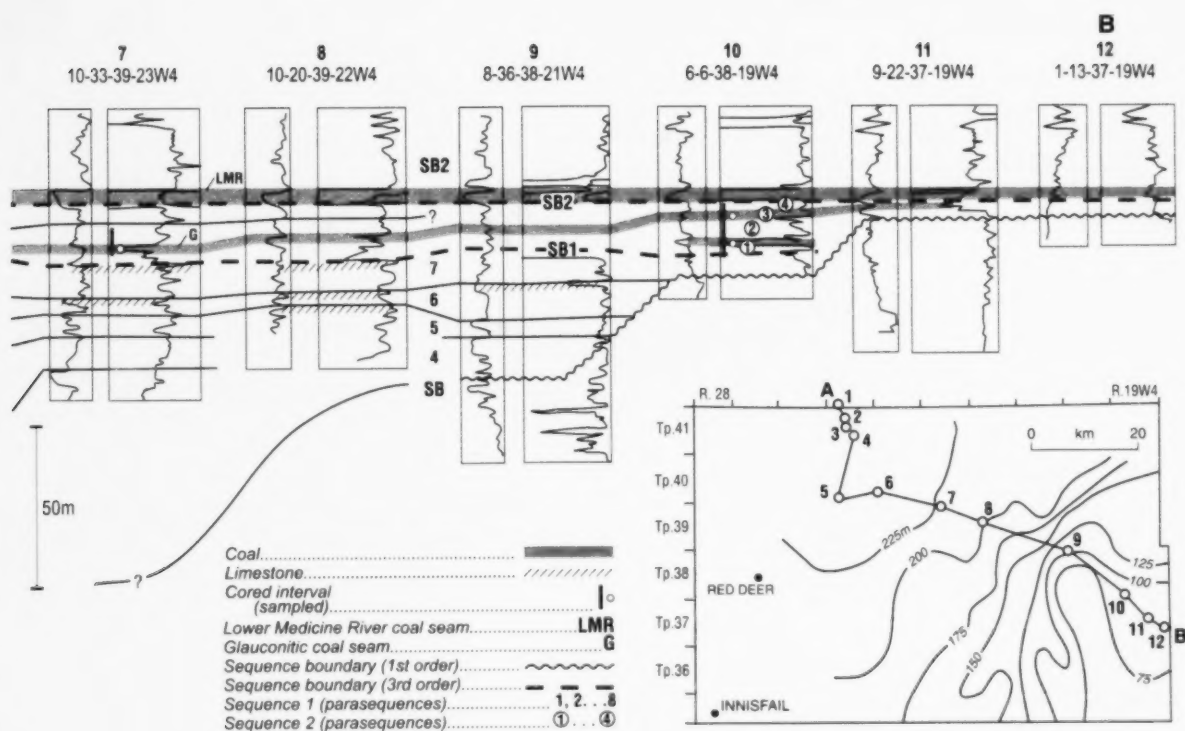


Figure 25 continued.

5. The vitrinite reflectances show a general trend to somewhat higher values in the top part of the seam. The decrease in reflectance at the very top of the seam may be related to a brief flooding event at the top corroborating palynological evidence (see below).
6. Mineral matter appears to decrease toward the top of the seam, suggesting a lower frequency of flooding events in the precursor mire and consequently lesser influx of clastics.

Palynology of the LMR seam, upper leaf

The palynological profile (Fig. 27, last column) shows an evolution of paleocommunities from a *Zygnema* freshwater marsh to *Gleichenia* dry marsh between 1569.0 and 1562.0 m and suggests a regressive phase. But a brief period of flooding is indicated between 1562 and 1560 m by the presence of marine dinoflagellates and *Polypodium* saltwater marsh. A brief flooding event seems to have succeeded the regressive seam.

The G seam

As the correlation in Figure 25 shows (wells 10, 11, and 12), the G seam represents a series of splits off the LMR seam. The base of all these splits is an unconformity surface. This is the third-order sequence boundary (Fig. 8) separating third-order sequences 1 and 2 located just above the dolomitized lime-mudstone bed at the top of the Ostracode zone. The G seam (Fig. 24b) successively splits basinward (NW).

According to the Twin Coal depositional model (Banerjee et al., 1996) (Fig. 18), the G seam (or the precursor mire, in the strict sense) was formed in a transgressive environment. The stratigraphic evidence is provided by the fact that the G seam is overlain by marine shale (Fig. 13, 14, 28) in most of the cored intervals illustrated in Figure 25. The G seam also exhibits a characteristic transgressive signature as shown in the detailed petrographic, chemical, and palynological analyses of samples from well 10-25-40-25W4 (Fig. 29).

Table 2
Maceral composition in vol.% (m.m.f.) and mineral matter
contents (vol.%) of the LMR seam, lower leaf, well 10-25-40-25W5

Lith	(mm)	Vitrinite								Inertinite				Liptinite					
		Ct	Cg1	Cd	Cg2	Vd	TV	Sf	F	Id	Ma	Mi	Tl	Sp	Cu	Re	Ot	TL	
DB	20	29	3	29			61	9	12	10		2	33	2		3		6	
DB	23	13	4	27	1	1	46	12	26	9	1	1	49	4				4	
D	57			2		2	4	4	18	72			93	2			2	4	
D	56	4		11		1	16	25	25	27	3	2	81	2				2	
Ptg																		0	
D	49	3				1	4	20	12	61			93	3				3	
DB	17	3		3		1	7	29	18	38	1		86	6				6	
DB	16	10		18			28	24	20	20	1	2	67	4				4	
Bd	20	27	1	31			59	8	12	15	1	1	37	3		1		5	
D	64	8	2	34			45	21	16	12			49	5				5	
D	18					3	3	24	41	32			97					0	
Ptg	7				Not analyzed														
D	25					5	5	7	29	56			93	2				2	
Br	10	65	6	13			84	2	6	6			13	2		1		3	
D	13	12		14		7	34	12	16	36			63	3				3	
BBr	15	58	3	18		1	79	3	2	11			16	1	4			5	
D	30	4		2		7	14	29	12	42			83	3				3	
Ptg	5	Parting																	
D	30	5		9		5	18	26	5	42	2	1	75	7	1			7	
BBr	5	54	8	18	1		82	1	3	2		2	9	2	3	3		8	
Bd	37	19	2	33	2		56	11	15	11	2	1	39	3	1			4	
Br	7	92	7				99						0			1		1	
Bd	23	34	1	32	2		68	7	11	10	1	1	30	1	0	1		2	
BBr	17	60	6	15	1		82	3	3	3	1		11	2	1	4		7	
Bd	5	41	6	24	1		72	5	9	5	3		21	3	3	2		7	
Bd	22	14	1	37			53	10	22	6	2		40	6				6	
BBr	6	39	2	35	1		77	5	8	7			20	2	1			3	
Fusain lens		1		5			6	29	47	10	3		90	4				4	
Bd	15	30	1	32		1	63	7	10	13	2		32	5				5	
Br	6	89	6	1			96						0			4		4	
DB	16	6		8		1	16	22	36	20	2	1	81	3				3	
Br	5	71	6	10			87		1	9		3	13						
D	17	6		13		3	23	28	18	24	1	2	73	5				5	
D	20			2		2	4	21	32	40			93	3				3	
Ptg					Lenticular parting														
D	17	2		3		2	7	12	27	49			88	5				5	
DB	5			Not analyzed															
Br	5	39	2	48			89		2	6			8	1	1			2	
D	5	6		12		6	24	20	15	36	1		72	3				3	
Br	12	49	5	35	3		91	1	3	2		1	7	2				2	
BBr	11	29	1	29	1		60	19	13	4	2	1	39	1				1	
D	35	9		9		1	19	28	14	37			78	2				2	
D	38	6		7		2	16	32	13	33	2		80	4		1		4	
Bd	40	33	1	31			65	12	9	10		1	32			1		1	
Bd	10	21	1	26			48	21	15	12	3		50			2		2	
D	10	32		39			71	8	9	12		1	29	1				1	
DB	20	12	1	29			43	18	15	19	1	1	54	3				3	
DB	35	14	1	27	1		43	14	19	19	1	2	55	3				3	
Br	5	67	6	8			81	1	5	11		1	18	1				1	
Bd	10	21		34		1	56	10	12	17		2	42	1				1	

Ct: collotelinite; Cg1: collotelinite, in situ; Cd: collotelinite; Cg2: collotelinite, detrital; Vd: vitrodetrinite; TV: total vitrinite; Sf: semi-fusinite; F: fusinite; Id: inertodetrinite; Ma: macrinite; Mi: micrinite; Tl: total inertinite; Sp: sporinite; Al: alginite; Cu: cutinite; Re: resinite; Ot: other liptinite, undifferentiated; TL: total liptinite; Br: bright coal; BBr: banded bright; DB: banded coal; Bd: banded dull coal; D: dull coal; Ptg: parting; Qtz: quartz; Clay: clay minerals; Carb: carbonate; Py: pyrite; TMM: total mineral matter; TPI: tissue preservation index; GI: gelification index

Table 2 cont.

Lith	(mm)	Minerals				TMM	TPI	GI
		Qtz	Clay	Carb	Py			
DB	20					0	1.8	1.3
DB	23					0	0.4	0.5
D	57	27	11	2		41	1.5	0.1
D	56	1				1	1.3	0.2
Ptg						0		
D	49	20	20	4		44	0.6	0.0
DB	17	7	1			8	0.1	0.5
							0.4	0.2
DB	16		2			2	0.4	0.6
Bd	20			3		3	1.0	1.7
D	64		1			1	1.0	0.9
D	18	19	3	2		24	1.9	0.0
Ptg	7					100		
D	25	8	29	4		42	0.6	0.1
Br	10					0	4.3	6.2
D	13	11	4			15	0.7	0.5
BBr	15	1	1			3	2.3	5.0
D	30	17	3			20	0.9	0.2
Ptg	5					100		
D	30	8	1			10	0.6	0.3
BBr	5					0	3.1	12.1
Bd	37		1			1	1.0	1.6
Br	7		4			4		
Bd	23						1.2	2.5
BBr	17		4			4	3.5	8.3
Bd	5						1.9	4.1
Bd	22	1	1			1	1.1	1.5
BBr	6	1	1			1	1.3	3.9
Fusain lens							4.3	0.1
Bd	15	1	2			3	1.0	2.1
Br	6						75.0	
DB	16						2.0	0.2
Br	5	1	1			1	4.2	8.4
D	17	4	1			5	1.3	0.3
D	20	9	3			12	1.2	0.0
Ptg						100		
D	17	18	4			21	0.8	0.1
DB	5							
Br	5						0.8	10.9
D	5	13				13	0.7	0.4
Br	12						1.4	13.8
BBr	11						1.7	1.7
D	35	6				6	1.1	0.2
D	38	3				3	1.1	0.2
Bd	40	0	1			1	1.3	2.1
Bd	10	3	1			3	1.4	1.1
D	10		1		24	24	1.0	2.5
DB	20	0	0			1	1.0	0.8
DB	35		3			3	1.0	0.8
Br	5	1	1			1	4.3	4.8
Bd	10						0.8	1.4

Petrography of the G seam

The coal seam was sampled in 7 consecutive column samples and was analyzed by image analysis for gross petrographic composition (maceral groups and mineral matter) and reflectance variations from seam base to seam top. Additionally, conventional maceral analysis was carried out to determine type of macerals and to calculate facies-critical ratios such as TPI and GI indices.

Results from image analysis are shown in Figure 29. The lithotype log shows a high variability in dull and bright bands throughout the seam (Fig. 29A), reflecting the gross petrographic composition of the seam as indicated in Figure 29B. Bright lithotypes dominate where vitrinite content is high, whereas the dull lithotypes are related to increasing amounts of mineral matter (Dm in Fig. 29A) or increase in inertinite macerals (Di in Fig. 29A).

The seam base is dominated by vitrinite macerals (40–50 cm, Fig. 29B), with a high vitrinite/inertinite ratio. Above that interval, relatively unstable conditions must have prevailed during peat accumulation, with a larger input of clastic minerals (interval 30–40 cm). Above that interval mineral matter contents are generally low, and a trend from inertinite-rich coal to vitrinite-rich coal can be observed (30–10 cm, Fig. 29B, C). The top portion of the seam above the parting shows again a larger input of mineral matter and the domination of vitrinite macerals prior to the drowning of the mire.

Random vitrinite reflectances were determined on 41 clean bands of collotelinite (Fig. 29F). The values were averaged to represent 1 mm intervals of the seam, and range from 0.61–0.78%. Highest vitrinite reflectances were recorded for the central portion of the seam, in particular the interval characterized by relatively low vitrinite content (30–40 cm, Fig. 29C). The reflectances are in general significantly lower at the seam base and at the seam top.

Results from maceral analysis of the columnar samples are shown in Table 4 and selected parameters derived from the analysis are plotted in Figure 29G, H, I. Gross petrographic composition of the seam (Table 4) compares favourably with the results obtained from image analysis (Fig. 29B).

Within the vitrinite group collotelinite and collodetrinite are the most common constituents (Table 4). Corpogelinite occurs in-situ (Cg1, Table 4) and in detrital form (Cg2). Vitrodetrinite occurs in minor to moderate amounts throughout the seam (Table 4), except at the very top, where it makes up 11 Vol% of the organic matter.

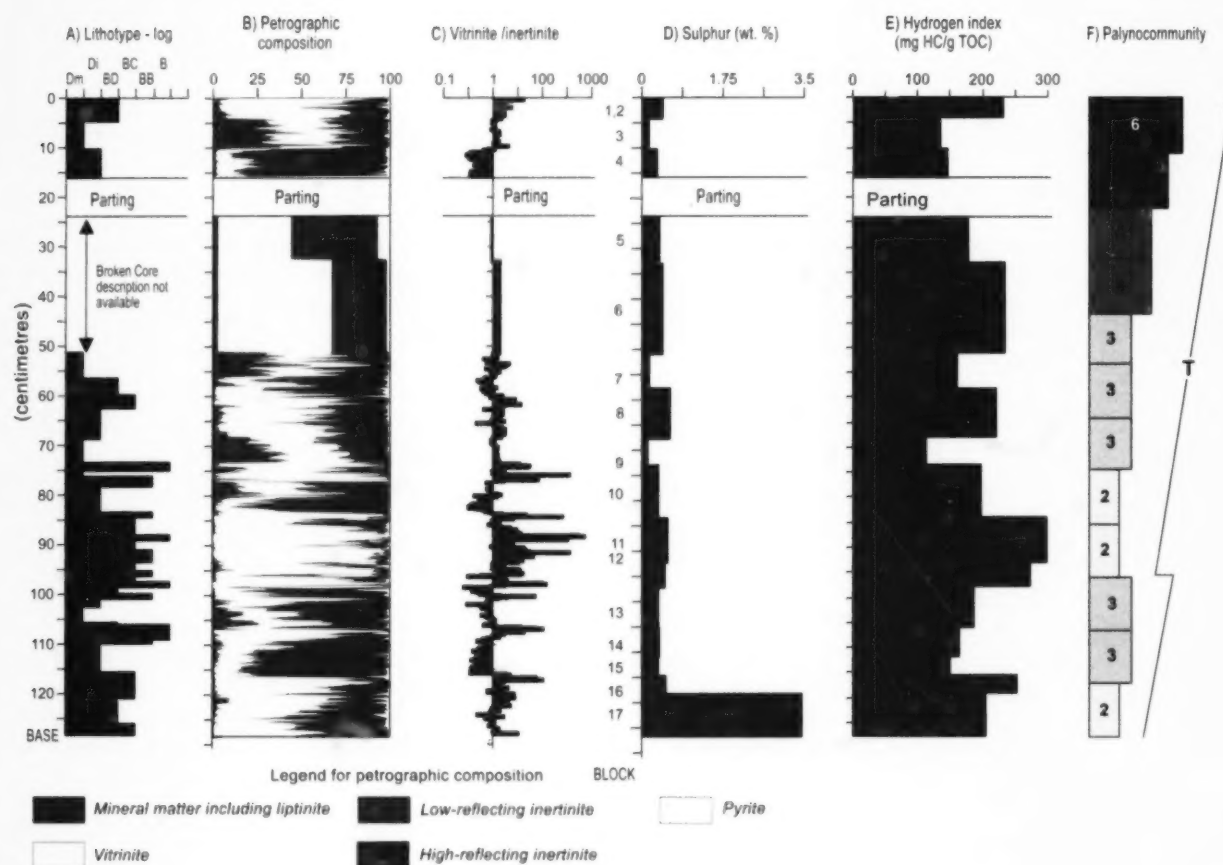


Figure 26. Coal character profiles (petrographic, geochemical, and palynological) in the bottom 1.2 m of the lower leaf of the LMR seam in well 10-25-40-25W4 (Fig. 13, 25). Compared to the ideal signature of a transgressive seam this figure shows a partial one (compare with the bottom half of the profiles of transgressive seams in Fig. 19a). For palynology legend see Figure 19b. T - transgression, R - regression.

Table 3
Maceral composition in vol.% (m.m.f.) and mineral matter contents of the LMR seam, upper leaf, well 6-7-40-24W4 (abbreviations for macerals and minerals same as Table 2)

Sample	Vitrinite						Inertinite				Liptinite				Minerals			TMM	TPI	GI	Ro (%)	
	Ct	Cd	Vd	VT	Sf	F	Id	Ma	Mi	IT	Sp	Al	Ld	LT	Qtz	Clay	Carb					Pyr
563/94			16	16	6	1	71			79	3	2	1	5	14	4			18	0.08	0.21	0.779
564/94		5	12	17	9	4	63			76	6	1		7	12	2			14	0.16	0.22	0.84
565/94		2	17	18	11	2	61			74	5	2		7	9	1			11	0.16	0.24	0.80
566/94			16	16	7	2	67			76	7	1		7	7	13			20	0.11	0.21	0.76
567/94		22	4	26	7	2	54	1	1	64	8			9					0	0.11	0.43	0.79
568/94		1	18	18	1	1	66			68	8	3	4	15	15	35		1	51	0.02	0.26	
569/94	1		39	40	6	2	47			55	2	1	2	5	23	24			47	0.10	0.73	0.75
570/94			39	39		1	55			57	1	1	2	4	11	44	13	2	70	0.01	0.70	0.81
571/94			20	20			74			74	2	2	2	6	41	39	1		82	0.00	0.27	
573/94	1	15	9	26	8	4	54	1		68	5	1	1	7	8	2			10	0.16	0.41	0.76
574/94	4	8	1	14	39	10	32	2		83	3			3	4	1		1	6	1.23	0.20	0.75
575/94	22	31		53	15	16	13	1	1	45	2			2		1			1	1.18	1.23	0.75

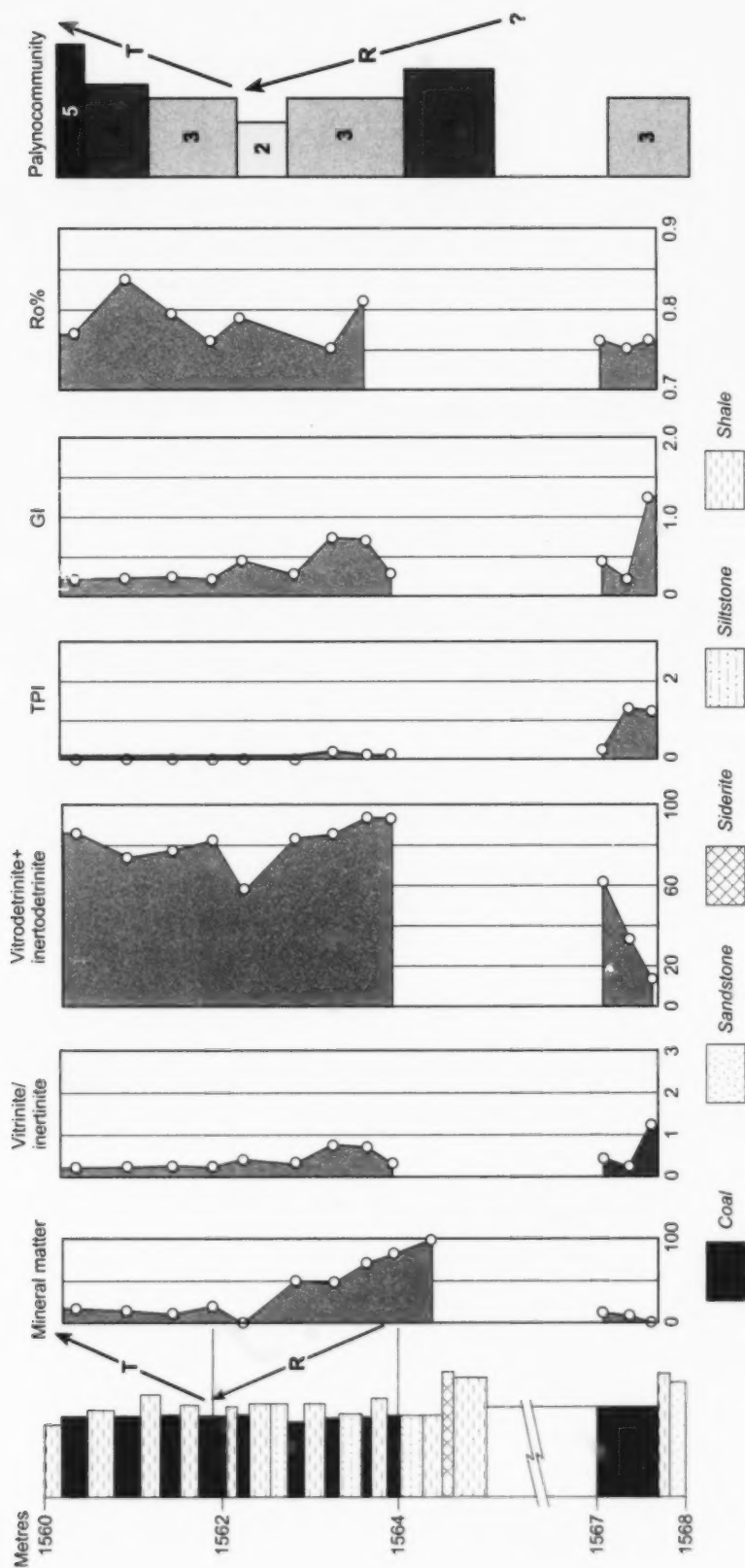


Figure 27. Petrographic profile of the upper leaf of the LMR coal seam in the 06-07-40-24W4 well. The profile compares favourably with an ideal regressive coal seam as shown in Figure 19a. For palynology legend see Figure 19b. T - transgression, R - regression. See text for explanation.

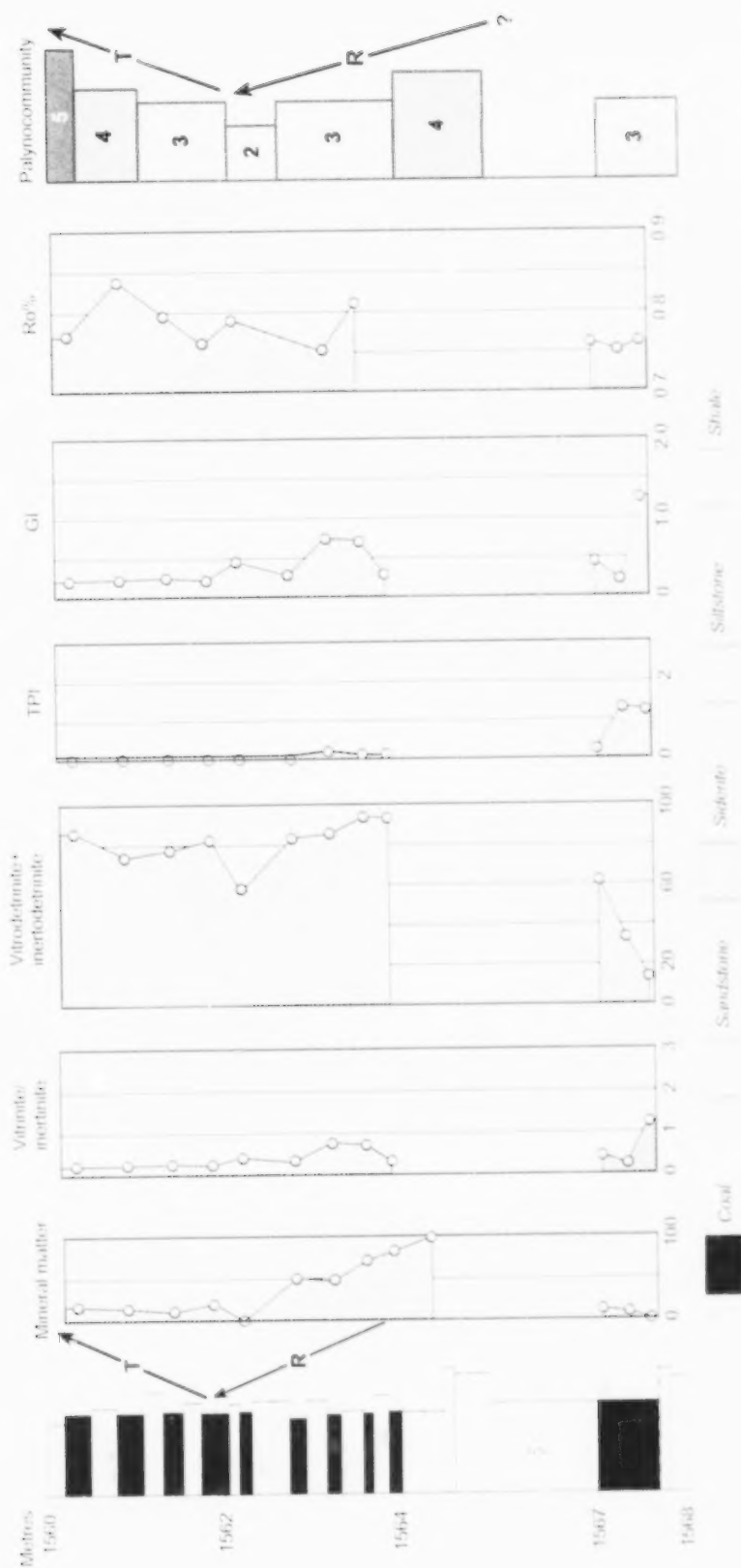


Figure 27. Petrographic profile of the upper level of the LMR coal seam in the 06-07-40-24W4 well. The profile compares favourably with an ideal regressive coal seam, as shown in Figure 19a. For palynology legend see Figure 19b. T - transgression, R - regression. See text for explanation.

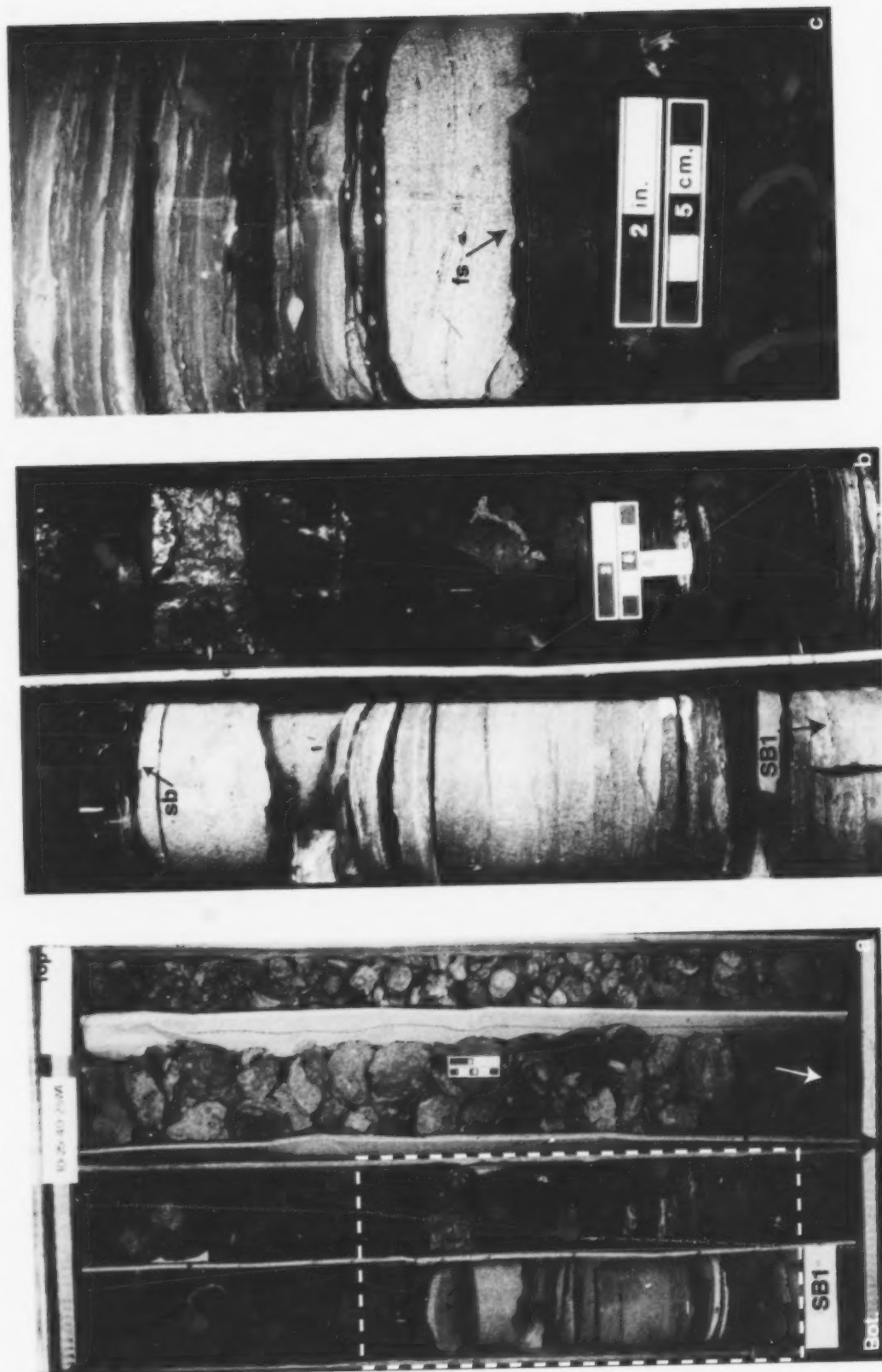


Figure 28. Core photographs illustrating the detailed stratigraphic relationship between the G seam and adjacent sedimentary strata. **a.** A parasequence or coarsening-upward sequence overlying a flooding surface that coincides with the third-order sequence boundary (SB1) on top of the Ostracode zone. A fine-grained sandstone and the G seam make up the rest of the unit, which is overlain by the next flooding surface (white arrow) (GSC photo no. 4609-14). **b.** An enlarged view (slightly rotated) of the boxed area in **a**. The depositional lag deposited on the surface of the third-order sequence boundary can be seen (SB1, black arrow). The base of the G seam is a fourth-order sequence boundary (sb). The right-hand column of **b** gives a detailed view of the G seam. Well 10-25-40-25W4, bottom of the core (Bot.) at 1572 m. (GSC photo 4609-15). **c.** Flooding surface (fs) on top of the G seam in well 10-28-38-19W4 at 1282.0 m. Burrowed sedimentary strata above the coal zone show a marine influence indicating the transgressive origin of the G seam (GSC photo no. 4609-33).

Table 4
Lithotype log, maceral analysis (vol% m.m.f.), mineral matter contents and TPI and GI
values for the G seam, well 10-25-40-25W4 (abbreviations for macerals and minerals same as Table 2)

values for the G seam, well 10-25-40-25W4 (abbreviations for lithology and mineralogy are given in the Appendix)																													
Block	Litho (mm)	Vitrinite										Inertinite					Liptinite					Minerals							
		Ct	Cg1	Cd	Cg2	Vd	TV	SI	F	Id	Ma	Mi	Ti	SP	Cu	Re	Ot	TL	Qtz	Clay	Carb	Pyr	TMM	TPI	GI				
1A	DB	8	28	1	35	4	11	79	5	1	14		1	21				1	5	10		6	21	0.5	3.9				
																							50						
	Ptg	16	Approx 50% organics																					3	18	0.7	2.2		
	Dm	10	21	1	32	2	7	63	9	7	12			28	7	1		1	9	6	8		3	10	0.9	18.4			
1B	DB	10	34	7	36	4	3	83			5			5	8	3			12	3	4								
																							70						
	Dm	12	Approx 30% organics																										
	BD	27	31	6	45	3	2	86	2	3	4			10	2	1	1		4	3	1	1	2	7	0.8	8.9			
2	Bd	3	Not analyzed																										
	Br	7	90					90									10		10										
	BBr	17	64	2	21	1		88	6		1			6	3		3		6	1			2	2	3.2	14.4			
	Di	15	12		28		1	41	14	17	21	1	1	53	5				5	3			1	4	0.8	0.8			
3	BBr	25	54	2	25	1		82	6	4	3			13	2				5	3									
	BBr	5	Not analyzed																										
	Br	5	8	4				92									8		8						2	0.9	0.6		
	DB	15	10		22		1	33	19	16	23	1		59	7				7	1									
4	Br	5	91	1				92						0			8		8										
	BBr	14	43	1	27	1		72	9	9	4	2		25	2	1	1		3	1			1	2	1.9	3.2			
	D	13	9		9		8	26	22	17	32			71	3				3	22	11			33	1.0	0.4			
	Br	7	90					90									10		10										
5	Bd	20	20		18		3	41	21	14	21			57	1				1	11	3	2		16	1.3	0.7			
	Bd	7	Not analyzed																										
	Di	35	12	1	19		1	32	16	24	23	1		64	4				4	2				2	1.2	0.5			
	Bd	7	16		3		6	25	27	19	27			73	1			1	2	12	4			16	1.8	0.3			
6a	Br	5	91		3			94									6		6										
	Dm	33	9		2		6	18	17	15	48			80	2				2	20	17		3	39	0.7	0.2			
	Br	3	98					98									2		2										
	Dm	17	6		4		4	14	17	19	48	1		84	2			1	2	19	11		1	31	0.7	0.2			
6b	Dm	19	5				3	8	8	25	53			86	3			3	6	19	21			41	0.7	0.1			
	Br	6	64		1		2	68	12	3	15			30	1	1	1		2	2				2	4.2	2.3			
	Di	15	9		12		2	24	18	14	35			68	7	1			8	13	2			15	0.8	0.4			
	BBr	25	30		23			53	24	5	10	2		41	4				5	1				1	1.7	1.4			
7a	BBr	26	39	3	37	2		81	7	6	3			15	3				4	2	1			2	1.3	5.3			
		32	32	3	43	1		79	5	6	5	1		17	2	1	1		4	2				2	0.9	5.0			
	Bd	7	35	2	34		2	72	4	9	8	1		22	5		1		6	5	7		1	13	1.1	3.5			
	Dm	14	Parting (rare organics)																							100			
7b	Br	7	23	8	48	7		86	2	3	3			8	5			1	6	2				2	0.6	10.8			
	BBr	9	5	7	23		4	87	1	5	4			10	2				3		11		1	12	2.2	8.8			

The inertinite group consists of semifusinite, fusinite, inertodetrinite, and macrinite (Table 4). Inertinite macerals, in particular inertodetrinite, are abundant in the Dm and Di lithotypes (Table 4), where they make up to 86 Vol% of the organic matter.

The liptinite group consists of sporinite, cutinite and resinite (Table 4), ranging from 1–12 Vol%. Mineral matter consists mainly of quartz and clay minerals, and minor carbonate. Pyrite values range from nil to 6 Vol% at the seam

top (Table 4), consistent with the high sulphur contents shown in Fig. 29D).

Tissue preservation indices (TPI) range from 0.5–2.8 and show a definite trend to lower values towards the seam top (Fig. 29H). The trend indicated by the range in gelification indices (GI) follows essentially that of the overall vitrinite content, suggesting wetter conditions in the mire at the seam base and top (Fig. 29I).

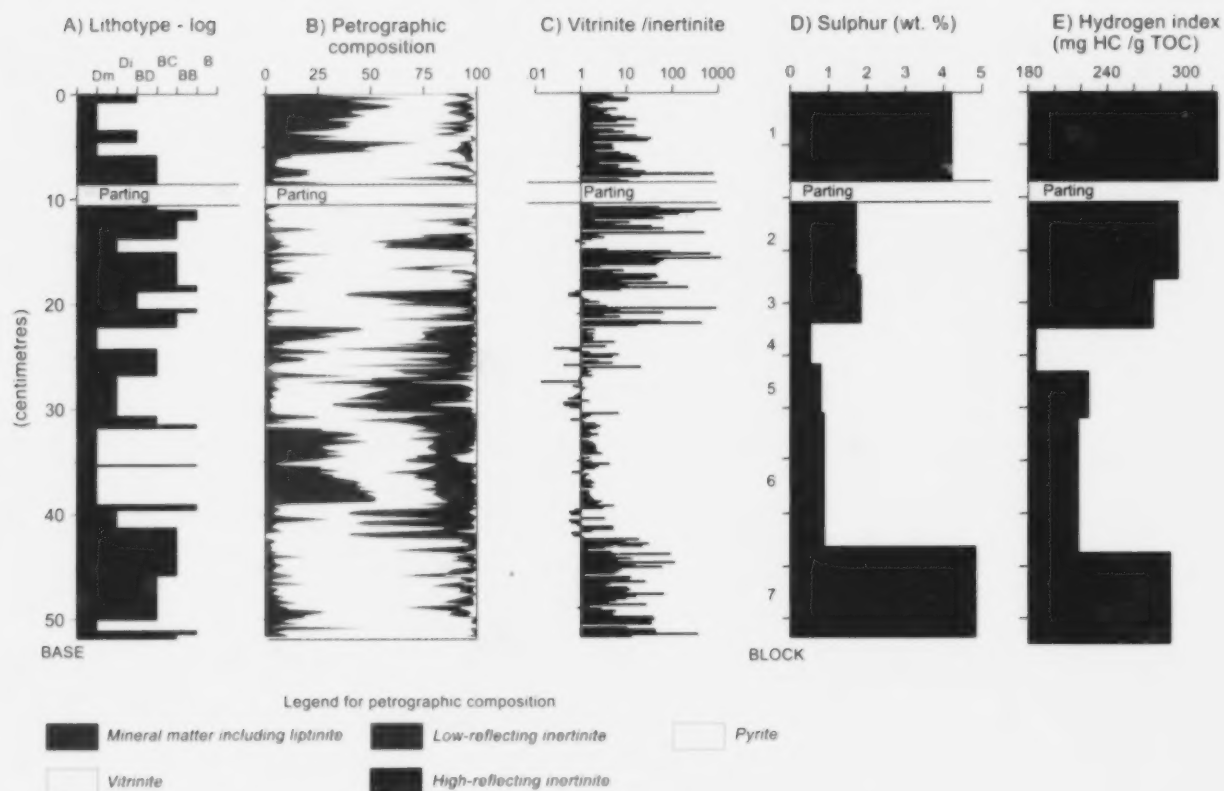


Figure 29. Coal character profiles of the G seam in well 10-25-40-25W4. Both the petrographic and palynological characteristics compare well with those of an ideal transgressive seam (Fig. 19). T - transgression, R - regression, TPI - tissue preservation index, averaged values, GI - gelification index, averaged values.

Geochemistry of the G seam

Geochemical analyses included sulphur determination and Rock-Eval pyrolysis. Sulphur contents are highest in intervals close to the top and base of the seam (4.2 and 4.8 wt. %, respectively, Fig. 29D). The higher concentration of sulphur at the top is an effect of the drowning of the mire by the advancing sea and that at the base might indicate either a brackish marine influence during initial peat accumulation or entrapment of sea water percolating from above at the permeability barrier at the base of the seam. Lowest sulphur content (0.54 wt. %) occurs in the central portion of the seam. Hydrogen indices show a similar pattern (Fig. 29E). Highest values occur at the base and top of the seam reflecting the overall higher vitrinite contents in these seam intervals. Lowest hydrogen indices occur in those seam intervals characterized by larger concentrations of inertinite macerals.

The petrographic and geochemical parameters suggest formation of the G seam in a overall transgressive setting and

compare favourably to the model profile of a transgressive seam (Fig. 19a): increase of vitrinite, sulphur (pyrite), and hydrogen toward the top, and a corresponding decrease in TPI and random reflectances.

Palynology of the G seam

The transgressive signature of the G seam is corroborated by the palynological analysis in the 10-25-40-25W4 well (Fig. 29J) and suggests an oscillating transgressive depositional environment. Out of the four other wells studied, three demonstrate weak transgression signatures and one, with only two samples analyzed, does not support any conclusion.

Coal seam profile of the amalgamated coal seam

A continuous cored interval through the thick, regionally extensive amalgamated LMR-UMR seam in the Ewing

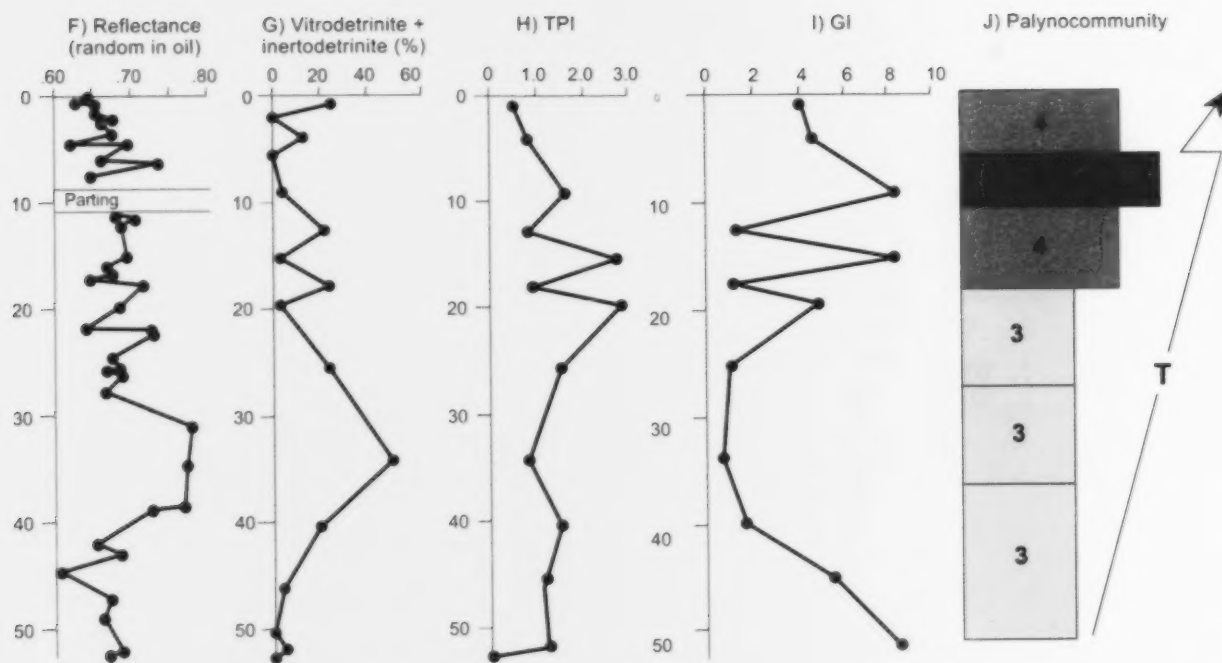


Figure 29 continued.

Lake well (07-01-37-21W4) was available for detailed analysis. Continuous columnar samples of the 12 m thick seam were cut from the core perpendicular to bedding for organic petrological analyses. In addition, 64 spot samples were collected for sulphur analysis at 0.2 m intervals and 38 spot samples were collected from 0.2–0.3 m intervals for palynological analyses. The detailed sampling of this thick seam provided analytical data that reveals the complexities of the amalgamated Medicine River seam.

Well 07-01-37-21W4 is located on a structural basement high. Basinward or downdip from the well (Fig. 24a) the seam splits into an upper (UMR) and a lower (LMR) leaf separated by a shale parting. The parting thickens basinward to a thickness of approximately 20 m of what seems from the log expression to be homogeneous sandstone, and maintains that thickness. In the cored well the thin end of the parting is a 1.2 m thick, fissile pyritiferous black shale with coal lenses.

The geophysical logs of this well show (Fig. 30) several physical contacts that divide the interval into four coaly and

three non-coaly units, suggesting four coal-forming episodes separated by three flooding events. Only the major shale parting at 1356.6–1358.0 m (Fig. 31) is visible in the core. The other two partings are suggested by two inertodetrinite horizons in the petrological profile at 1354.0–1354.3 m and 1360.9–1361.2 m (Fig. 32).

Cycles within the amalgamated Medicine River seam

As already mentioned, the cored interval of well 07-01-37-21W4 shows two unconformities, one revealed by palynology at 1358 m at the transgressive base of the shale parting, which is a third-order sequence boundary separating the UMR (above) from the LMR (below). Another third-order sequence boundary occurs at the seam base as indicated by a rooted paleosol horizon with angular chert clasts (Fig. 33). This sequence boundary is regionally extensive (Fig. 9a, below the LMR). A fourth-order sequence boundary occurs at 1360.80 m, separating the regressive phase of the lower leaf from the overlying

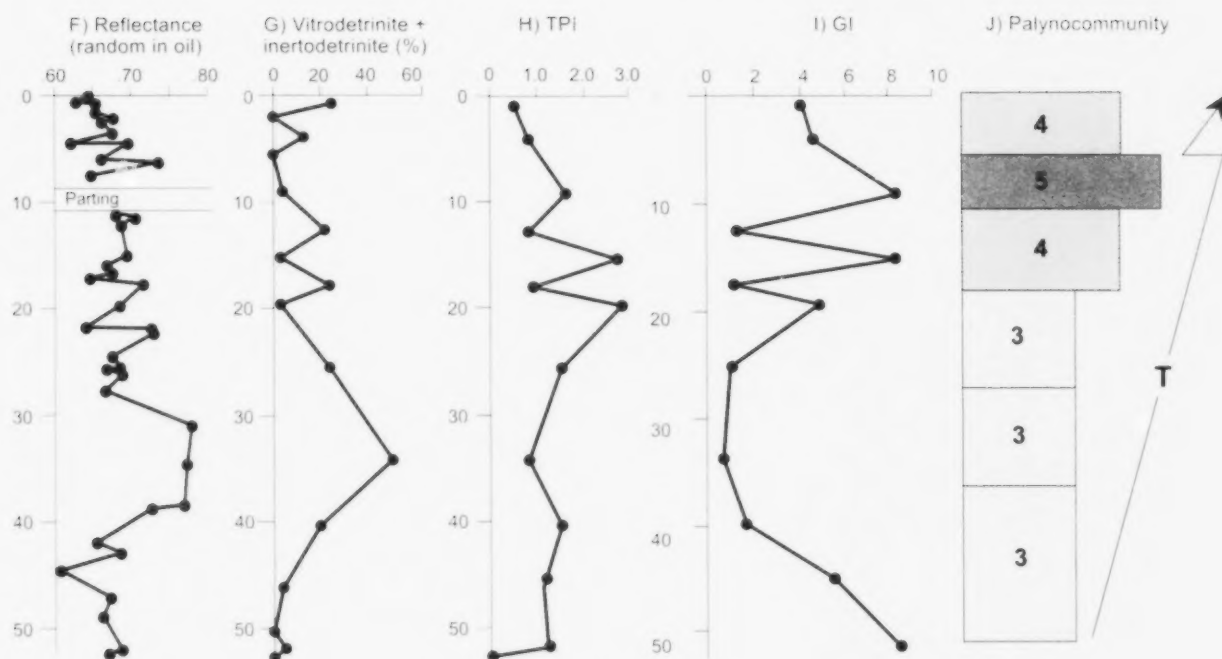


Figure 29 continued.

Lake well (07-01-37-21W4) was available for detailed analysis. Continuous columnar samples of the 12 m thick seam were cut from the core perpendicular to bedding for organic petrological analyses. In addition, 64 spot samples were collected for sulphur analysis at 0.2 m intervals and 38 spot samples were collected from 0.2–0.3 m intervals for palynological analyses. The detailed sampling of this thick seam provided analytical data that reveals the complexities of the amalgamated Medicine River seam.

Well 07-01-37-21W4 is located on a structural basement high. Basinward or downdip from the well (Fig. 24a) the seam splits into an upper (UMR) and a lower (LMR) leaf separated by a shale parting. The parting thickens basinward to a thickness of approximately 20 m of what seems from the log expression to be homogeneous sandstone, and maintains that thickness. In the cored well the thin end of the parting is a 1.2 m thick, fissile pyritiferous black shale with coal lenses.

The geophysical logs of this well show (Fig. 30) several physical contacts that divide the interval into four coaly and

three non-coaly units, suggesting four coal-forming episodes separated by three flooding events. Only the major shale parting at 1356.6–1358.0 m (Fig. 31) is visible in the core. The other two partings are suggested by two inertodetrinite horizons in the petrological profile at 1354.0–1354.3 m and 1360.9–1361.2 m (Fig. 32).

Cycles within the amalgamated Medicine River seam

As already mentioned, the cored interval of well 07-01-37-21W4 shows two unconformities, one revealed by palynology at 1358 m at the transgressive base of the shale parting, which is a third-order sequence boundary separating the UMR (above) from the LMR (below). Another third-order sequence boundary occurs at the seam base as indicated by a rooted paleosol horizon with angular chert clasts (Fig. 33). This sequence boundary is regionally extensive (Fig. 9a, below the LMR). A fourth-order sequence boundary occurs at 1360.80 m, separating the regressive phase of the lower leaf from the overlying

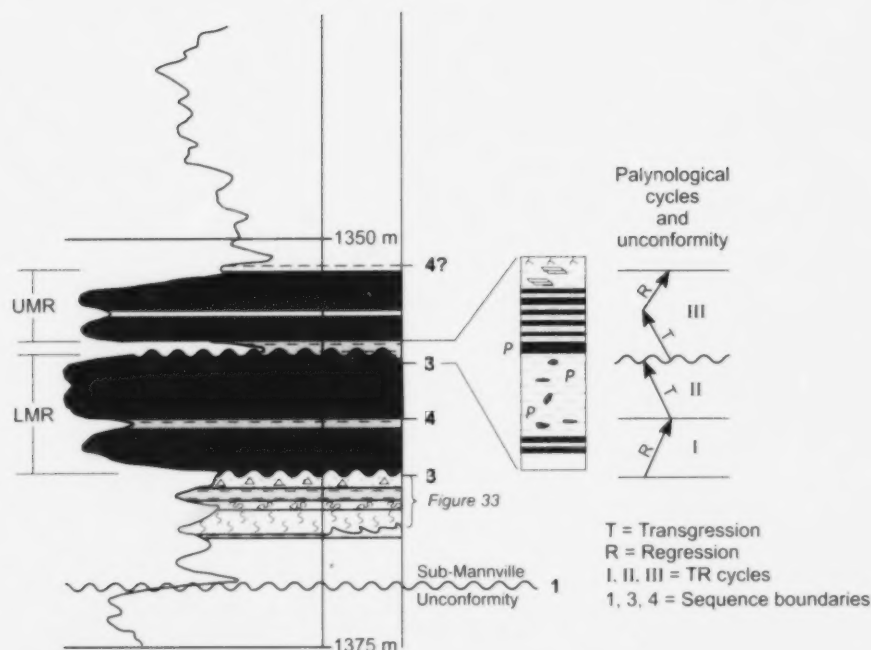


Figure 30. Core and geophysical (gamma-ray) logs of well 07-01-37-21W4, showing locations of three orders of sequence boundaries (first, third, and fourth) as revealed by lithological breaks in the amalgamated Medicine River seam. On the right, one complete and two incomplete TR cycles are shown. Two unconformities, one indicated from palynological analysis (at 1358 m, at the base of a 1.20 m thick pyritiferous black shale parting with coal lenses) and the other from the presence of a rooted paleosol horizon seen in the core (Fig. 33) have been detected.

transgressive phase. The palynological profile of the UMR seam drawn from palynofloral succession based on miospore assemblages reveals at least three major TR cycles (Fig. 32).

Petrography of the amalgamated Medicine River seam

The petrographic composition of the seam was determined by automated image analysis. The results are graphically represented in Figure 31, showing for each increment the relative proportions in contents of mineral matter and liptinite, vitrinite, and low-, medium-, and high-reflecting inertinite (from left to right, scale is in volume per cent). The raw data compiled in excel spread sheets were used to determine full seam characteristics and the petrographic compositions of the lower and upper leaves, and to determine petrographic characteristics of seam subsections and relate these characteristics to TR cycles within the seam as indicated from palynological and sequence-stratigraphic analyses (Table 5).

Full seam characteristics

Petrographic data for the full seam and for the upper and lower leaves separated by the major shale parting are listed in Table 5. According to these data the seam has an overall vitrinite content of 58.7%, an inertinite content of 30.8%, and mineral matter and liptinite constitute 10.5%. The upper leaf has slightly higher vitrinite and mineral matter and liptinite contents, when compared to the full seam characteristics (Table 5), whereas the lower leaf shows the opposite trend. The gross petrographic composition of full seam and lower and upper leaves is typical for many Lower Cretaceous coals from the Western Canada Sedimentary Basin, which originated in peats accumulating in a coastal strandplain setting (Kalkreuth and Leckie, 1989).

In-seam variations and TR cycles

The petrographic profile of the seam (Fig. 31) indicates a complex structure, with vitrinite-rich layers alternating with inertinite-rich zones. Mineral matter and liptinite contents

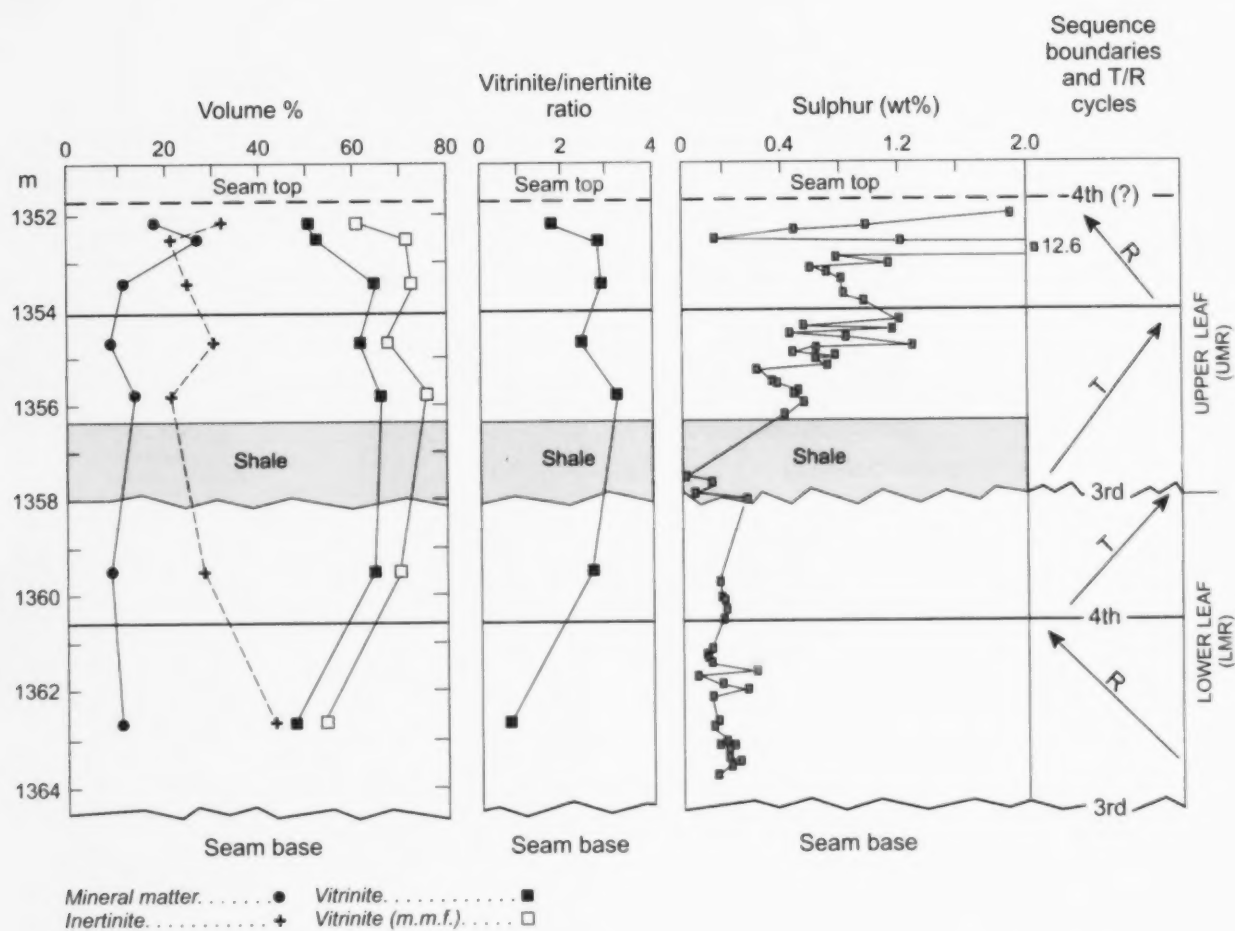


Figure 31. Petrographic characteristics, sulphur content, sequence boundaries and TR cycles for the amalgamated Medicine River seam in well 07-01-37-21W4. See text for explanation.

contribute to a lesser extent to the petrographic composition of the seam, except in a few thin layers in the upper portion, where these two constituents make up to 50–60%.

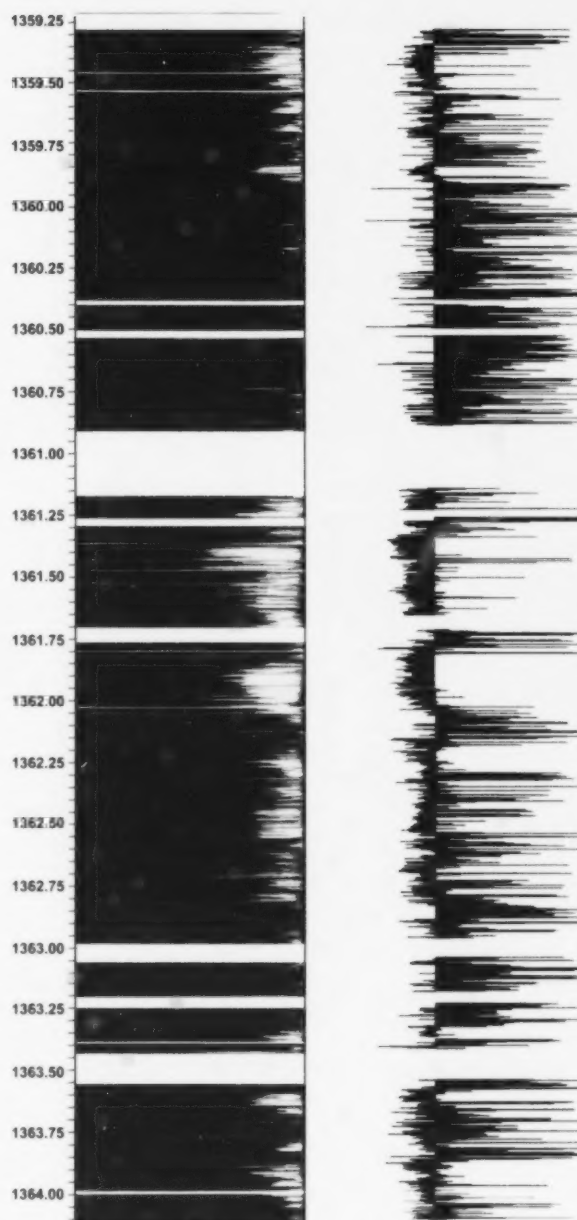
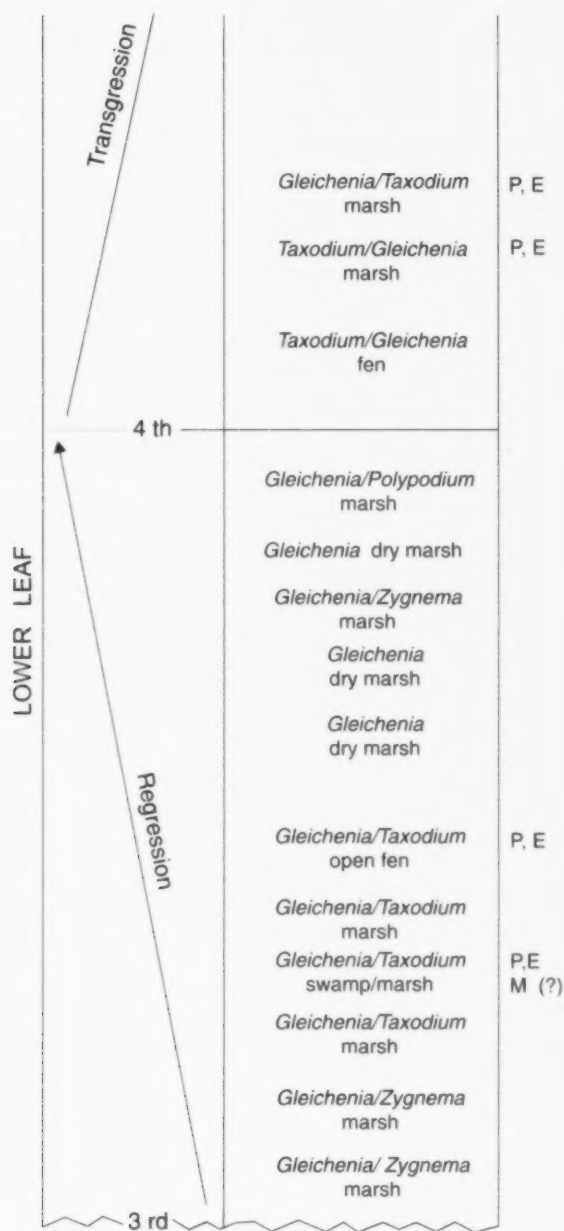
The following discussion describes the petrographic seam properties with respect to TR cycles as indicated by palynological analyses and sequence-stratigraphic concepts.

Lower leaf

The base of the lower leaf (LMR) was formed in a regressive setting followed by a transgressive phase separated from the former by a fourth-order sequence boundary (Fig. 32). Within the regressive cycle the seam is characterized by relatively high amounts of inertinite, in particular in the top part (1361.3–1362.8 m, Fig. 31). The overall petrographic composition in the regressive cycle of the lower leaf is: 47.5% vitritine, 42.7% inertinite, and 9.8% mineral matter and liptinite (Table 5). Based on palynomorph assemblages,

peat formation at the base of the regressive cycle took place in *Taxodium-Gleichenia-Zygnema* swamps and marshes, possibly under marine influence (Fig. 32), whereas at the top of the interval a trend to drier conditions (*Gleichenia* dry marsh) was recorded. This trend to generally drier conditions is also reflected by the increasing inertinite content at the top of this interval.

The petrographic composition of the overlying transgressive cycle is significantly different, with a predominance of vitritine, except in some central parts of this interval (1359.40–1359.75 m, 1359.90–1359.95 m and at the very top (Fig. 32). The average composition in the transgressive part of the lower leaf is: 64.4% vitritine, 27.6% inertinite, and 8.0% mineral matter and liptinite (Table 5). Mire types range from *Taxodium/Gleichenia* fens at the base (Fig. 32) to brackish swamps and marshes at the top, reflecting the overall wetter conditions during peat accumulation. The differences in vitritine and inertinite contents between the two depositional settings can also be



Vertical increment: 5 cm

P = ponding
E = euryhaline dinoflagellates
D = marine dinoflagellates
B = brackish
M = marine

Liptinite/mineral matter	Medium-reflecting inertinite
Vitrinite	High-reflecting inertinite
Low-reflecting inertinite	Parting

Figure 32 continued.

seen in the profile of vitrinite/inertinite ratios (Fig. 32), which clearly demonstrates the predominance of vitrinite over inertinite in the transgressive phase (average V/I ratio of 2.5), whereas the regressive phase at the base of the lower leaf shows as a consequence of higher inertinite contents an average V/I ratio of 1.6.

Upper leaf

The upper leaf (UMR) forms part of a TR cycle (Fig. 31) including a major shale parting at the base, which in turn is underlain by a third-order sequence boundary. The initial phase of the transgressive cycle (1355.05–1356.49 m) is characterized by many thin alternating vitrinite-rich and inertinite-rich layers. The average vitrinite content is 66.0%, inertinite content is 20.8%, and mineral matter and liptinite content is 13.1%. The predominance of the vitrinite group continues seam-upward, with an average value of 61.7% (top of transgressive interval, 1354.92–1355.00 m) and in the basal part of the overlying regression phase (64.7%, 1352.88–1352.98 m), with V/I ratios of 2.04 and 2.64, respectively. From this level on, a significant decrease of average vitrinite content can be observed in the upper regression intervals at the top of the upper leaf (52.4% and 50.6%; Table 5), while inertinite contents increase. Palynomorph assemblages indicate for this transgressive phase a change from freshwater marshes and *Taxodium* swamps at the base (Fig. 32) to brackish and salt water marshes at the top as suggested by the occurrence of euryhaline and marine dinoflagellates. The regression phase

is characterized by fluctuating water table heights as indicated by a *Zygnema* freshwater marsh at the base (Fig. 32), followed by a *Taxodium/Gleichenia* dry fen environment. This in turn is overlain by a seam interval that was formed in a lagoonal fen-marsh environment, before seam development ended in a *Taxodium/Gleichenia* dry fen paleoenvironment. The change to drier conditions is also reflected by the increasing inertinite contents noted for this uppermost interval (Fig. 32).

Vitrinite has its origin in predominantly woody tissues that are transformed into humic acids in the early stages of diagenesis under relatively moist and reducing conditions, whereas inertinite components are thought to have been formed in drier conditions prone to atmospheric oxidation and bacteria and fungal attack (Taylor et al., 1998). For the UMR seam it can be demonstrated that during transgressive cycles vitrinite is the predominant organic component (Fig. 32), suggesting a relatively high water table during peat accumulation. During regressive phases of peat accumulation vitrinite contents appear to decrease at the expense of inertinite. This is in particular evident at the base of the lower seam and at the top of the upper leaf (Fig. 32).

Distribution of sulphur content

High sulphur content in coal is in general taken to reflect peat accumulation in proximity to the sea, with marine incursions providing sulfate for reduction to sulfide and the consequent formation of pyrite (Casagrande et al., 1979; Casagrande,

Table 5
Average petrographic characteristics for the amalgamated Medicine River seam in well 07-01-37-21W4 based on automated image analysis

SB	TR cycles	Top (m)	Base (m)	Thick. (m)	MM	Vitr	Inert 1	Inert 2	Inert 3	Vitr/Inert	Vitr	Inert 1	Inert 2	Inert 3
4th (?)														
	Top regression (top)	1352.03	1352.30	0.27	17.6	50.6	17.5	9.5	4.8	1.59	61.4	21.2	11.5	5.8
	Top regression (middle)	1352.30	1352.74	0.44	26.7	52.4	13.4	5.3	2.2	2.51	71.5	18.3	7.2	3.0
	Top regression (base)	1352.88	1353.98	1.10	10.7	64.7	14.7	7.2	2.6	2.64	72.5	16.5	8.1	2.9
	Top transgression (top)	1354.29	1355.00	0.71	8.1	61.7	18.4	9.2	2.6	2.04	67.1	20.0	10.0	2.8
	Top transgression (base)	1355.05	1356.49	1.44	13.1	66.0	11.6	6.5	2.7	3.17	75.9	13.3	7.5	3.1
3rd														
	Base transgression	1358.03	1360.91	2.88	8.0	64.4	16.5	8.9	2.2	2.33	70.0	17.9	9.7	2.4
4th														
	Base regression	1361.17	1364.12	2.95	9.8	47.5	24.8	16.1	1.8	1.11	52.7	27.5	17.8	2.0
3rd														
Seam Characteristics														
	Upper leaf	1352.03	1356.49	4.46	12.7	62.3	14.7	7.5	2.7	2.50	71.4	16.8	8.6	3.1
	Lower leaf	1358.03	1364.12	6.09	8.9	56.0	20.6	12.5	2.0	1.60	61.5	22.6	13.7	2.2
	Full seam	1352.03	1364.49	12.46	10.5	58.6	18.1	10.4	2.3	1.90	65.5	20.2	11.6	2.6

MM = Mineral matter; Inert1 = low-reflecting inertinite; Inert2 = medium-reflecting inertinite; Inert3 = high reflecting inertinite; m.m.f. = mineral-matter-free basis; Vitr/Inert = vitrinite/inertinite - ratio; Vitr = vitrinite

1987). Enrichment of sulphur has also been observed at the very top of coal seams and has been linked to influence of overlying marine strata (Williams and Keith, 1963, Diessel, 1992). Within the mire the height of the water table also has a significant impact on sulphur formation. In times when the

water table is relatively low, a high redox potential and low pH may retard bacterial sulphur reduction resulting in low H_2S levels, and pyrite formation is limited. In times of high water tables the opposite may occur.

The amalgamated seam has relatively low sulphur content in the lower leaf (LMR) (< 0.8 wt%). The values are in particular low in the regressive phase of peat formation (Fig. 31), with an average value of 0.41 wt. %. These low values suggest that the peat at this stage was in general well protected from marine influence. These results are in agreement with earlier studies by Kalkreuth and Leckie (1989) and Langenberg et al. (1989), which also noted low sulphur contents in correlative Gates coals to the north as a consequence of a well-protected coastline. The basal part of the transgressive phase has low sulphur values (average is 0.41 wt.%) similar to those of the underlying regressive coal. At the top, in proximity to the overlying marine shale parting the sulphur content increases to 0.57 wt. %.

In the upper leaf of the amalgamated seam the sulphur values are in general higher (except at the very base, Fig. 31), with many intervals having sulphur values > 1.0 wt. %. The transgressive phase of the upper leaf shows a clear trend to increasing sulphur content upseam, from 0.17–0.36 wt. % at the base to maximum values of > 1.6 wt. % at the top (average is 0.92 wt. %).

In the overlying regressive phase the sulphur values initially decrease (Fig. 31), and are followed by very high sulphur values recorded in a sample from a shale parting (12.6 wt.%) and at the very top of the seam (2.40 wt. %, Fig. 31), suggesting a marine influence for these intervals. It appears that in this phase of peat accumulation the mire was prone to marine inundations despite the fact that the depositional environment as a whole was regressive. The overall greater marine influence during peat accumulation of the upper leaf is also confirmed by results from palynological analyses (Davies, 1995, pers. comm.), which indicate a lagoonal setting and the occurrence of euhaline dinoflagellates at 1352.57 m, corresponding approximately to the depth level for which the high sulphur value of 12.6 wt. % was determined.

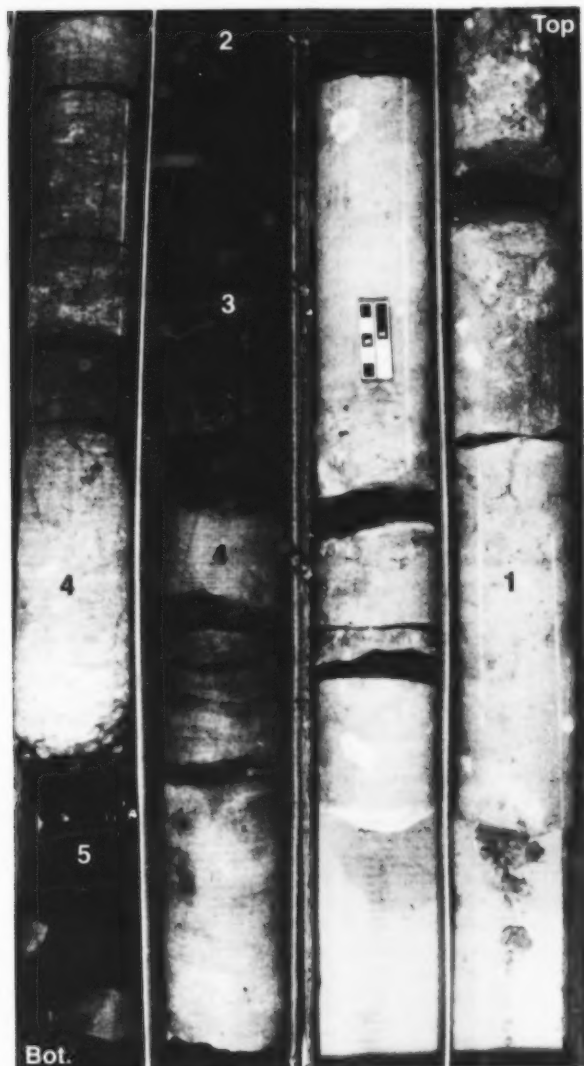


Figure 33. Core photograph of the 2.9 m thick strata underlying the amalgamated Medicine River seam in well 07-01-37-21W4 (Fig. 30). The top is at 1365.0 m and the bottom is at 1367.9 m. The core shows (from top to bottom): 1) rooted, mottled, structureless, very fine-grained sandstone (paleosol) with angular chert clasts set in a clayey matrix; 2) shaly coal (8 cm) bright/dull with well-developed cleats; 3) dark laminated shale with coal lenses; 4) deformed, burrowed and flow-folded siltstone with numerous plant fragments and possible rootlets with a sharp, undulatory top and a loaded base; and 5) fissile, organic-rich black shale (GSC photo no. 4609-31).

Coal seam sequence stratigraphy

The detailed study of the regionally extensive, thick amalgamated seam also reveals another aspect of coal seam sequence stratigraphy. As illustrated in the model in Figure 21, it is apparent that toward the shallower, landward end of the basin, many higher order sequence boundaries (fourth-order) would probably merge landward into a single lower (third-order) order boundary produced by an erosional surface at the top of a progradational platform. So the stacked fourth-order sequence boundaries below the LMR

seam (Fig. 24a) probably merges with regional third-order sequence boundary. Many thick regionally extensive paralic seams should exhibit this phenomenon. The third-order sequence boundary below the LMR also merges with the one below the UMR (Fig. 24a).

In conclusion, the detailed study of the petrological, geochemical and palynological profiles of the amalgamated seam at well 07-01-37-21W4 demonstrates that successive coal-seam splits produced by single TR cycles merge landward in step-like fashion to produce thick seams; these TR coal couplets are bounded by fourth-order sequence boundaries that merge landward into one third-order sequence boundary; and as a result of the above merger of single couplets into a thick seam, regional seams such as the amalgamated seam should exhibit multiple TR cycles, and several minor (fourth-order) and at least one major (third-order) unconformity.

CONCLUSIONS

In the subsurface the Lower Cretaceous Mannville Group, which constitutes a second-order sequence, can be divided into six third-order sequences based on variations in stratal patterns, the presence of incised valleys and their relation to regional coal seams, and lithological evidence of unconformities. Coal seams overlie third-order sequence boundaries (which coincide with the transgressive surfaces) in most cases.

Four major regional coal seams with numerous minor splits and thin, discontinuous local seams occur in the Upper Mannville subgroup, which is located in the highstand systems tract of the second-order Mannville Sequence.

An integrated study of the palynological, petrographic, and geochemical characters in the three seams studied (the LMR, UMR and G seam), reveals that these splits represent high-frequency (fourth-order) sequences produced in single transgressive-regressive (TR) cycles stacked as a series of progradational wedges within subhorizontal third-order sequence boundaries.

Continuous columnar samples from a cored interval through the entire Medicine River seam (07-01-37-21W4 well) provided detailed analytical data. These data revealed a complex coal seam profile consisting of at least three TR (one entire and two partial) cycles and two unconformities (third-order sequence boundaries), and a fourth-order sequence boundary. Stratigraphic cross-sections in the area of the well show that fourth-order sequences merge landward to produce the thicker amalgamated seam, and fourth-order sequence boundaries (minor unconformities) also merge landward to form a single major unconformity marking a third-order sequence boundary. The above

relations found within thick, regionally extensive coal seams may provide a solution for the enigma of thick (>5 m) coal seams (Shearer et al., 1994).

REFERENCES

- Aitken, J.F.
1995: Utility of coal seams as genetic stratigraphic sequence boundaries in nonmarine basins: an example from the Gunnedah Basin, Australia; discussion; American Association of Petroleum Geologists, Bulletin, v. 79, p. 1179-1181.
- Aitken, J.F. and Flint, S.S.
1994: High frequency sequences and the nature of incised valley fills in fluvial systems of the Breathitt Group (Pennsylvanian), Appalachian foreland basin, eastern Kentucky; in *Incised Valley Systems: Origin and Sedimentary Sequences*, (ed.) R. Dalrymple, R. Boyd and B. Zaitlin; Society of Economic Paleontologists and Mineralogists Special Publication 51, p. 353-368.
- 1995: The application of high resolution sequence stratigraphy to fluvial systems: a case study from the Upper Carboniferous Breathitt Group, eastern Kentucky, U.S.A.; *Sedimentology*, v. 42, p. 3-30.
- Arditto, P.A.
1991: A sequence stratigraphic analysis of the Late Permian succession in the Southern Coalfield, Sydney Basin, New South Wales; *Australian Journal of Earth Sciences*, v. 38, p. 125-137.
- Banerjee, I.
1986: Lower Mannville sedimentation in the "Edmonton Channel", central Alberta; in *Current Research, Part B; Geological Survey of Canada, Paper 86-1B*, p. 383-397.
- 1990: Some aspects of Lower Mannville sedimentation in southeastern Alberta; *Geological Survey of Canada, Paper 90-11*, 40 p.
- Banerjee, I. and Davies, E.H.
1988: An integrated lithostratigraphic and palynostratigraphic study of the Ostracode zone and adjacent strata in the Edmonton Embayment, central Alberta; in *Sequences, Stratigraphy, Sedimentology: Surface and Subsurface*, (ed.) D.P. James and D.A. Leckie; Canadian Society of Petroleum Geologists, Memoir 15, p. 261-274.
- Banerjee, I. and Kidwell, S.M.
1991: Significance of Molluscan shell beds in sequence stratigraphy: an example from the Lower Cretaceous Mannville Group of Canada; *Sedimentology*, v. 38, p. 913-934.
- Banerjee, I. and Raychaudhuri, I.
1996: Paleoenvironmental significance of biota of the Ostracode zone (Mannville Group) in south-central Alberta; in *Current Research Part E, Geological Survey of Canada, Paper 96-1E*, p. 111-122.
- Banerjee, I., Kalkreuth, W.D., and Davies, E.H.
1995: Sequence stratigraphy of coal with examples from the Mannville Group in central Alberta; in *Proceedings of the Oil and Gas Forum '95 - Energy from Sediments*, (ed.) J.S. Bell et al.; Geological Survey of Canada, Open File 3058, p. 151-157.

- 1996: Coal seam splits and transgressive-regressive coal couplets: a key to stratigraphy of high-frequency sequences; *Geology*, v. 24, p. 1001-1004.
- Banerjee, I., Ghosh, S.K., Abercrombie, H.J., and Davies, E.H.**
1994: An integrated subsurface study of the Mannville-Colorado group boundary in the Cessford Field Alberta; *Canadian Journal of Earth Sciences*, v. 31, p. 489-504.
- Brownridge, S. and Moslow, T.F.**
1991: Tidal estuary and marine facies of the Glauconitic Member, Drayton Valley, central Alberta; in *Clastic Tidal Sedimentology*, (ed.) D.G. Smith, G.E. Reinson, B.A. Zaitlin, and R.A. Rahmani; Canadian Society of Petroleum Geologists, Memoir 16, p. 107-122.
- Bustin, R.M. and Smith, G.G.**
1993: Coal deposits in the Front Ranges and foothills of the Canadian Rocky Mountains, southern Canadian Cordillera; *International Journal of Coal Geology*, v. 23, p. 1-27.
- Bustin, R.M., Cameron, A.R., Grieve, D., and Kalkreuth, W.**
1985: Coal Petrology - Its Principles, Methods and Applications; Geological Association of Canada, Short Course Notes, v. 3, Victoria, B.C., 2nd ed., 273 p.
- Caldwell, W.G.E., Diner, R., Eicher, D.L., Fowler, S.P., North, B.R., Stelck, C.R., and von Holdt Wilhelm, L.**
1993: Foraminiferal biostratigraphy of Cretaceous marine cyclothems; in *Evolution of the Western Interior Basin*, (ed.) W.G.E. Caldwell and E.G. Kauffman; Geological Association of Canada, Special Paper 39, p. 477-520.
- Cant, D. and Abrahamson, B.**
1996: Regional distribution and internal stratigraphy of the Lower Mannville; *Bulletin of Canadian Petroleum Geology*, v. 44, p. 508-529.
- Cant, D.J. and Stockmal, G.S.**
1989: The Alberta foreland basin: Relationship between stratigraphy and Cordilleran terrane-accretion events; *Canadian Journal of Earth Sciences*, v. 26, p. 1964-1975.
- Casagrande, D.**
1987: Sulphur in peat and coal; in *Coal and Coal-Bearing Strata: Recent Advances*; Geological Association Special Publication 32, (ed.) A. Scott, p. 87-105.
- Casagrande, D., Grout, K., and Sutton, N.**
1979: The distribution of sulphur and organic matter in various fractions of peat: origins of sulphur in coal; *Geochimica and Cosmochimica Acta*, v. 44, p. 25-32.
- Casagrande, D., Cohen, A., Given, P., and Spackman, W.**
1974: The comparative study of the Okefenokee swamp and the Everglades-Mangrove swamp-marsh complex of southern Florida; Geological Society of America Annual Meeting Field Trip 6, University Park, Pennsylvania State University Coal Research Section, 265 p.
- Chiang, K.K.**
1984: The giant Hoadley gas field, south-central Alberta; in *Elmworth - Case Study of a Deep Basin Field*, (ed.) J.A. Masters; American Association of Petroleum Geologists, Memoir 38, p. 297-313.
- Coates, E.J., Groat, C.G., and Hart, G.F.**
1980: Subsurface Wilcox Lignite in west-central Louisiana, Gulf Coast Association of Geological Societies Transactions, v. 30, p. 309-332.
- Cross, T.A.**
1988: Controls on coal distribution in transgressive-regressive cycles, Upper Cretaceous, Western Interior, U.S.A.; in *Sea-level Changes: An Integrated Approach*, (ed.) C.K. Wilgus, B.S. Hastings, C.G. St. C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner; Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 371-380.
- Dawson, F.M. and Kalkreuth, W.D.**
1994: Coal rank distribution and coalbed methane potential of the Lower Cretaceous Luscar Group, Bow River to Blackstone River, central Alberta Foothills; Geological Survey of Canada, Bulletin 473, 52 p.
- Diessel, C.F.K.**
1992: Coal-bearing Deposition Systems; Berlin, Springer-Verlag, 721 p.
- Elliot, R.E.**
1969: Deltaic processes and episodes. The interpretation of productive coal measures occurring in the East Midlands, Great Britain; *Mercian Geologist*, v. 3, p. 111-135.
- Embry, A.F.**
1995: Sequence boundaries and sequence hierarchies: problems and proposals; in *Sequence Stratigraphy on the Northwest European Margin*, (ed.) R.J. Steel et al.; NPF Special Publications 5, Elsevier, Amsterdam, p. 1-11.
- Ferm, J.C., Horne, J.C., Winchatt, J.P., and Whaley, P.W.**
1971: Carboniferous depositional environments in northeastern Kentucky; Geological Society of Kentucky Guidebook.
- Fielding, C.R.**
1986: The anatomy of a coal seam split, Durham coalfield, northeast England; *Geological Journal*, v. 21, p. 45-47.
1987: Coal depositional models for deltaic and alluvial plain sequences; *Geology*, v. 15, p. 661-664.
- Flint, S.S., Aitken, J.F., and Hampson, G.**
1995: The application of sequence stratigraphy to coal-bearing coastal plain successions: implications for the U.K. Coal Measures; in *European Coal Geology*, (ed.) M. Whatley and D.A. Spears; Geological Society of London Special Publication 82, p. 1-16.
- Fowler, M.G., Gentzis, T., Goodarzi, F., and Foscolos, T.**
1991: The petroleum potential of some Tertiary lignites from northern Greece as determined using pyrolysis and organic petrology techniques; *Organic Geochemistry*, v. 17, p. 805-826.
- Galloway, W.E.**
1989: Genetic stratigraphic sequences in basin analysis I. Architecture and genesis of flooding-surface bounded depositional units; American Association of Petroleum Geologists, Bulletin 73, p. 125-142.
- Galloway, W.E. and Hobday, D.K.**
1996: Terrigenous Clastic Deposition Systems; 2nd Edition, Springer-Verlag, Berlin-Heidelberg-New York, 489 p.

- Gastaldo, R.A., Demko, T.M., and Liu, Y.**
1993: Application of sequence and genetic stratigraphic concepts to Carboniferous coal-bearing strata: an example from the Black Warrior basin, U.S.A.; *Geologische Rundschau*, v. 82, p. 212–226.
- Gibling, M.R. and Bird, D.J.**
1994: Late Carboniferous cyclothems and alluvial paleovalleys in the Sydney Basin, Nova Scotia; *Bulletin of the Geological Society of America*, v. 106, p. 105–117.
- Hamilton, D.S. and Tadros, N.Z.**
1994: Utility of coal seams as genetic stratigraphic sequence boundaries in nonmarine basins: an example from the Gunnedah Basin, Australia; *American Association of Petroleum Geologists, Bulletin*, v. 78, p. 267–286.
- Hampson, G.**
1995: Discrimination of regionally-extensive coals in the Upper Carboniferous of the Pennine basin, U.K. using high-resolution sequence stratigraphic concepts; in *European Coal Geology*, (ed.) M. Whitley and D.A. Spears; *Geological Society Special Publication* 82, p. 79–97.
- Herbert, C.**
1997: Relative sea level control of deposition in the Late Permian Newcastle Coal Measures of the Sydney Basin, Australia; *Sedimentary Geology*, v. 107, p. 167–187.
- Holdgate, G.R. and Sluiter, I.R.K.**
1991: Oligocene-Miocene marine incursions in the Latrobe Valley depression, onshore Gippsland Basin: evidence, facies relationships and chronology; *Geological Society of Australia, Special Publication* 18, p. 137–157.
- Hughes, J.D.**
1994: Interpretative three-dimensional modelling and geological/economic analysis of layered sequences; *Papers and extended abstracts for technical programs, International Association for Mathematical Geology Annual Conference, Mont Tremblant, Quebec, Canada*, p. 154–168.
- ICCP**
1963: *International Handbook of Coal Petrography*, 2nd edition; International Committee of Organic and Coal Petrology, Centre National de la Recherche, Paris.
- ICCP**
1994: *Vitrinite Classification; International Committee for Organic and Coal Petrology, ICCP System 1994*, 24 p.
- Jackson, P.C.**
1984: Paleogeography of the Lower Cretaceous Mannville Group of Western Canada; in *Elmworth - A Case Study of a Deep-basin Gas Field*, (ed.) J.A. Masters; *American Association of Petroleum Geologists, Memoir* 38, p. 49–78.
- Kalkreuth, W.D. and Leckie, D.A.**
1989: Sedimentological and petrographical characteristics of Cretaceous strandplain coals: a model for coal accumulation in North American Western Interior Seaway; *International Journal of Coal Geology*, v. 12, p. 381–424.
- Kauffman, E.G.**
1980: Major factors influencing the distribution of Cretaceous coal in the Western Interior United States; in *Fourth Symposium on the Geology of Rocky Mountain Coal Proceedings*, (ed.) L.M. Carter; *Colorado Geological Survey, Resource Series* 10, p. 1–3.
- Kosters, E.C. and Suter, J.R.**
1993: Facies relationships and systems tracts in the late Holocene Mississippi Delta plain; *Journal of Sedimentary Petrology*, v. 63, p. 727–733.
- Kosters, E.C., Chmura, G.L., and Bailey, A.**
1987: Sedimentary and botanical factors influencing peat accumulation in the Mississippi Delta; *Journal of the Geological Society* 144, p. 423–434.
- Langenberg, C.W., Rottenfusser, B.A. and Richardston, R.J.H.**
1997: Coal and coalbed methane in the Mannville Group and its equivalents, Alberta; in *Petroleum Geology of the Cretaceous Mannville Group, Western Canada*, (ed.) S.G. Pemberton and D.P. James; *Canadian Society of Petroleum Geologists, Memoir* 18, p. 475–486.
- Langenberg, W., Macdonald, D., Kalkreuth, W., and Strobl, R.**
1989: Coal quality variation in the Cadomin-Luscar coalfield, Alberta; *Alberta Research Council Earth Science Report* 89-1, 65 p.
- Lawrence, D.T.**
1982: Influence of transgressive-regressive pulses on coal-bearing strata of the Upper Cretaceous Adaville Formation, southwestern Wyoming; in *Fifth Symposium on the Geology of Rocky Mountain Coal Proceedings*, (ed.) K.D. Gurgel; *Utah Geological and Mineral Survey, Bulletin* 118, p. 32–49.
- Leckie, D.A. and Smith D.G.**
1992: Regional setting, evolution and depositional cycles of the western Canada Foreland basin; in *Foreland Basins and Foldbelts*, (ed.) R.W. Macqueen and D.A. Leckie; *American Association of Petroleum Geologists, Memoir* 55, p. 9–46.
- Marchioni, D. and Kalkreuth, W.D.**
1991: Coal facies interpretations based on lithotype and maceral variations in Lower Cretaceous (Gates Formation) coals of Western Canada; *International Journal of Coal Geology* v. 18 p. 125–162.
- Marchioni, D., Kalkreuth, W.D., Utting, J., and Fowler, M.**
1994: Petrography, Palynology and Geochemistry of Hub and Harbour seams, Sydney Coalfield, Nova Scotia, Canada - implications for facies development; *Paleogeography, Paleoclimatology, Paleoecology*, v. 106, p. 241–270.
- McCabe, P.J. and Shanley, K.W.**
1992: Organic control on shoreface stacking patterns: bogged down in the mire; *Geology*, v. 20, p. 741–744.
- Posamentier, W. and Vail, P.R.**
1988: Eustatic controls on clastic deposition II - sequence and systems tract models; in *Sea-level Changes: An Integrated Approach*, (ed.) C.K. Wilgus, B.S. Hastings, C.G. St. C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner; *Society of Economic Paleontologists and Mineralogists, Special Publication* 42, p. 125–154.
- Pratt, K.**
1989: The use of automated image analysis to determine conventional coal petrographic parameters - An example from southeastern British Columbia; *Geological Survey of Canada, Contributions to Canadian Coal Science, Paper* 89-8, 137–145.

- 1993: The use of composite and mosaic imaging of polished surfaces to enhance petrographic analysis of coal by image analysis; *Organic Geochemistry*, v. 20, p. 759-768.
- Read, W.A.**
1995: Sequence stratigraphy and lithofacies geometry in an early Namurian coal-bearing succession in central Scotland; in *European Coal Geology*, (ed.) M.K.G. Whitley and D.A. Spears; Geological Society Special Publication No. 82, p. 285-297.
- Rosenthal, L.R.P.**
1988: Wave dominated shorelines and incised channel trends: Lower Cretaceous Glauconitic Formation, west-central Alberta; in *Sequences, Stratigraphy, Sedimentology: Surface and Subsurface*, (ed.) D.P. James and D.A. Leckie; Canadian Society of Petroleum Geologists, Memoir 15, p. 207-220.
- Ryer, T.A.**
1981: Deltaic coals of Ferron sandstone Member of Mancos Shale: predictive model for Cretaceous coal-bearing strata of Western Interior; *American Association of Petroleum Geologists, Bulletin*, v. 65, p. 2323-2340.
1984: Transgressive-regressive cycles and the occurrence of coal in some Upper Cretaceous strata of Utah, U.S.A.; in *Sedimentology of Coal and Coal-bearing Sequences*, (ed.) R.A. Tahamani and R.M. Flores; International Association of Sedimentologists, Special Publication 7, p. 217-227.
- Schneider, W.**
1984: Angewandte Palaobotanik und Braunkohlenpetrologie - Pflanzliche Gewebe als Gefügebildner in der Braunkohle; in *Beiträge zur Geologie und Erkundung von Kohlelagerstätten*, Freiburger Forschungsheft, v. C381, p. 14-25.
- Shearer, J.C., Staub, J.R., and Moore, T.A.**
1994: The conundrum of coal bed thickness: A theory of stacked mire sequences; *Journal of Geology*, v. 102, p. 611-617.
- Strobl, R.S.**
1988: The effects of sea level fluctuations on prograding shorelines and estuarine valley-fill sequences in the Glauconitic member, Medicine River field and adjacent areas; in *Sequences, Stratigraphy, Sedimentology: Surface and Subsurface*, (ed.) D.P. James and D.A. Leckie; Canadian Society of Petroleum Geologists, Memoir 15, p. 221-236.
- Taylor, G. Teichmüller, M., Davis, A., Diessel, C., Littke, R., and Robert, P.**
1998: *Organic Petrology*, Gebrüder Borntraeger, Berlin, 704 p.
- Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N., and Perez-Cruz, C.**
1991: The stratigraphic signatures of tectonics, eustasy and sedimentology - an overview; in *Cycles and Events in Stratigraphy*, (ed.) G. Einsele, W. Ricken and A. Seilacher; Springer-Verlag, New York, N.Y., p. 611-659.
- Van Wagoner, J.C., Mitchum, R.M., Jr., Campion, K.M., and Rahmanian, V.D.**
1990: Siliciclastic sequence stratigraphy in well logs, cores and outcrop; *American Association of Petroleum Geologists, Methods in Exploration*, v. 7, 55 p.
- Williams, E. and Keith, B.**
1963: Relationship between sulphur in coals and occurrences of marine roof beds; *Economic Geology*, 58, p. 720-729.
- Wood, J.M.**
1996: Sedimentology and sequence architecture of incised-valley fills and interfluvial deposits: upper Mannville interval (Lower Cretaceous), Little Bow - Turin area, southern Alberta; *Bulletin of Canadian Petroleum Geology*, v. 44, p. 632-654.
- Zaitlin, B.A., Dalrymple, R.W., Boyd, R., Leckie, D., and McEachern, J.**
1994: The stratigraphic organization of incised valley systems: implications to hydrocarbon exploration and production; *Short Course Notes*, Canadian Society of Petroleum Geologists, Calgary, Alberta, 189 p.

APPENDIX LIST OF CORES STUDIED

	Well location	Stratigraphic interval	Core depth	Length of core
1.	7-8-36-22W4	Ellerslie Fm	1564-1579 m	15 m
2.	6-27-36-21W4	Glaucinitic Sandstone	4768-4814 ft.	46 ft.
3.	6-24-37-23W4	Glaucinitic Sandstone	1494-1502 m	8 m
4.	3-25-37-23W4	Glaucinitic Sandstone	1509-1517 m	8 m
5.	10-28-38-19W4	Glaucinitic Sandstone	1265-1283 m	18 m
6.	6-12-38-21W4	Detrital	4227-4267 ft.	40 ft.
7.	10-14-38-21W4	Ostracode zone	1385-1403 m	18 m
8.	8-22-38-22W4	Ostracode zone - Ellerslie Fm	1399-1408 m	9 m
9.	9-16-38-23W4	Ostracode zone - Glaucinitic Sandstone	1470-1488 m	18 m
10.	14-35-38-23W4	Glaucinitic Sandstone	1423-1441 m	18 m
11.	11-15-38-24W4	Glaucinitic Sandstone	1532-1541 m	9 m
12.	12-17-36-19W4	Glaucinitic Sandstone	1287.2-1305.5 m	18.3 m
13.	7-21-36-21W4	Glaucinitic Sandstone	4675-4721 ft.	46 ft.
14.	4-27-36-24W4	Glaucinitic Sandstone	1660-1674 m	14 m
15.	6-34-37-23W4	Glaucinitic Sandstone	1502-1513 m	11 m
16.	6-6-38-19W4	Glaucinitic Sandstone	1270-1288 m	18 m
17.	9-9-38-23W4	Glaucinitic Sandstone	1480.6-1489.6 m	9 m
18.	6-34-38-24W4	Glaucinitic Sandstone	1530-1548 m	18 m
19.	14-21-39-22W4	Glaucinitic Sandstone	1363-1381 m	18 m
20.	14-21-39-22W4	Ostracode zone - Ellerslie Fm	1390-1408 m	18 m
21.	2-4-40-23W4	Glaucinitic Sandstone	1463-1477 m	14 m
22.	6-4-36-21W4	Glaucinitic Sandstone	4598-4653 ft.	55 ft.
23.	8-20-37-22W4	Glaucinitic Sandstone	1515-1532.5 m	17.5 m
24.	16-24-38-24W4	Glaucinitic Sandstone	1468.2-1481.8 m	13.6 m
25.	2-29-39-22W4	Glaucinitic Sandstone	1376-1389 m	13 m
26.	2-22-39-23W4	Glaucinitic Sandstone	4672-4702 ft.	30 ft.
27.	6-14-39-23W4	Glaucinitic Sandstone	1417-1430.3 m	13.3 m
28.	10-20-39-22W4	Glaucinitic Sandstone	1369-1387 m	18 m
29.	16-25-39-23W4	Glaucinitic Sandstone	1394.4-1411.6 m	17.2 m
30.	10-33-39-23W4	Glaucinitic Sandstone	4725-4755 ft.	30 ft.
31.	10-12-35-22W4	Ellerslie Fm - Ostracode zone	4894-4966 ft.	72 ft.
32.	6-33-35-25W4	Ostracode zone	5800-5850 ft.	50 ft.
33.	7-1-37-24W4	Ostracode zone	5102-5152 ft.	50 ft.
34.	3-8-40-23W4	Glaucinitic Sandstone	5111-5151 ft.	40 ft.
35.	2-35-40-24W4	Ostracode zone	1494-1504 m	10 m
36.	10-36-38-25W4	Glaucinitic Sandstone	1570-1588 m	17.9 m
37.	10-25-40-25W4	Glaucinitic Sandstone	1557-1584 m	27 m
38.	2-4-26-11W4	Glaucinitic Sandstone - Ellerslie Fm	1003.6-1020.6 m	14.6 m
39.	6-27-26-12W4	Glaucinitic Sandstone	3311-3371 ft.	60 ft.
40.	16-4-36-20W4	Medicine River Coal	1387-1418 m	5 m
41.	7-1-37-21W4	Medicine River Coal	1352-1367.3 m	15.1 m
42.	8-23-44-28W4	Glaucinitic Sandstone - Ellerslie Fm	1707-1725 m	18 m
43.	13-27-44-28W4	Glaucinitic Sandstone	1729-1746.3 m	16.8 m
44.	6-33-49-3W5	Ostracode zone	1605-1623 m	18 m

UNCONFORMITY CORES

Line 1

45.	6-32-29-14W4	Detrital - Nordegg Fm	1116.5-1131m	14.4 m
46.	8-36-30-16W4	Detrital - Banff Fm	1215-1223 m	7.9 m
47.	8-11-33-18W4	Detrital - Banff Fm	1286-1303 m	17 m
48.	8-15-33-18W4	Ellerslie Fm - Banff Fm	1265-1285 m	19.5 m
49.	16-20-33-18W4	Detrital - Banff Fm	1318.2-1328.5 m	9.4 m
50.	8-19-34-19W4	Detrital - Banff Fm	1343-1348 m	5 m

Line 2

51.	14-12-49-4W5	Detrital - Banff Fm	1668-1686.4 m	18.4 m
52.	8-22-49-4W5	Detrital - Nordegg Fm	1664-1690 m	26 m
53.	6-34-49-4W5	Detrital - Nordegg Fm	1632-1644 m	11.5 m
54.	6-9-50-5W5	Ostracode zone - Nordegg Fm	1607-1625 m	18 m
55.	8-36-50-5W5	Ostracode zone - Nordegg Fm	1597-1618.5 m	21.3 m
56.	6-10-56-8W5	Detrital - Nordegg Fm - Banff Fm	1589-1618.2 m	26.5 m
57.	14-7-57-9W5	Ostracode zone - Nordegg Fm	1612-1627 m	15 m
58.	8-9-33-25W4	Ellerslie Fm - Pekisko Fm	1692-1719 m	17.5 m
59.	6-36-39-3W5	Ostracode zone - Jura Sandstone	2134-2154.5 m	20.6 m
60.	9-26-47-9W5	Ellerslie Fm - Fernie Shale - Poker Chip Shale	2170-2199.5 m	28.1 m
61.	6-15-48-9W5	Ellerslie Fm - Fernie Shale - Rock Creek Fm - Poker Chip Shale	2108.6-2144.6 m	30 m
62.	6-19-48-9W5	Glauconitic Sandstone - Fernie Shale - Rock Creek Shale	2164-2199 m	35 m
63.	11-36-48-10W5	Ellerslie Fm - Rock Creek Fm - Poker Chip Shale	2224-2256 m	32 m
64.	7-11-49-10W5	Ellerslie Fm - Rock Creek Fm	2200-2208 m	8 m
65.	5-13-50-11W5	Ellerslie Fm - Rock Creek Fm	2214-2229 m	15 m
66.	6-34-50-11W5	Ellerslie Fm - Rock Creek Fm	2225-2246 m	21 m
67.	4-13-52-12W5	Glauconitic Sandstone - Rock Creek Fm	2128-2183 m	55 m
68.	11-22-52-12W5	Ellerslie Fm - Rock Creek Fm	2137-2187 m	50 m
69.	6-2-56-2W5	Basal Quartz - Detrital - Banff Fm		

MANNVILLE CORES (REGIONAL)

Line 1

70.	10-5-25-19W4	Glauconitic Sandstone - Basal Quartz	4562-46.. ft.	
71.	8-29-30-23W4	Glauconitic Sandstone - Basal Quartz	1589-1521 m	13 m
72.	11-28-40-24W4	Ostracode zone - Ellerslie Fm	5215-5304 ft.	89 ft.
73.	11-05-41-23W4	Ostracode zone - Ellerslie Fm	4796-51.. ft.	
74.	11-08-41-24W4	Ostracode zone - Ellerslie Fm	5002-51.. ft.	
75.	14-32-44-25W4	Ostracode zone - Ellerslie Fm	1463-1481 m	18 m
76.	7-1-37-21W4	Ostracode zone - Ellerslie Fm	1352-1367.3 m	15.1 m
77.	16-4-36-20W4	Glauconitic Sandstone - Ellerslie Fm	1387-1391, 1410-18 m	4+5 m
78.	13-27-44-28W4	Glauconitic Sandstone - Ostracode zone	1729-1746.3 m	16.8 m
79.	8-23-44-28W4	Ostracode zone - Basal Quartz	1707-1725 m	18 m
80.	6-27-26-12W4	Glauconitic Sandstone - Ostracode zone	3311-3371 ft.	60 ft.
81.	2-4-26-11W4	Glauconitic Sandstone - Ostracode zone - Coal	1003.6-1020.6 m	14.6 m
82.	6-33-49-3W5	Glauconitic Sandstone - Ostracode zone - Coal	1605-162 m	18 m

Line 2

83.	6-25-25-19W4	Basal Quartz	1444-1461.5 m	17.5 m
84.	10-12-24-18W4	Medicine River Coal	1219.5-1227 m	6.3 m
85.	6-34-25-19W4	(1) Basal Quartz, (2) Glauconitic Sandstone	1388-146, 1434-50 m	18, 16 m

86.	11-34-24-18W4	Upper Mannville Subgroup 4m below Medicine River	1332-1350 m	18 m
87.	8-5-26-19W4	N.A.		
88.	16-13-26-19W4	Glauconitic Sandstone	1421-1439 m	18 m
89.	12-15-27-20W4	Basal Quartz	1365-1393 m	18 m
90.	8-5-26-19W4			
91.	11-29-29-22W4	Glauconitic Sandstone(?)	1488-1506 m	18 m
92.	9-29-30-23W4	Ostracode zone	158.3-1521.3 m	11.2 m
93.	12-4-31-23W4	Ostracode zone - Basal Quartz	1557.5-1575.5 m	18 m
94.	7-33-34-27W4	Detrital	1915-1921 m	6 m
95.	14-28-36-28W4	Glauconitic Sandstone	1940-1958 m	18 m
96.	10-34-37-1W5	Pekisko Fm - Banff Fm	228-2048 m	18.9 m
97.	11-35-38-2W5	Detrital (?)	6900-6910 ft.	7 ft.
98.	8-10-40-3W5	Glauconitic Sandstone - Ostracode zone	2065.5-2083.3 m	17 m
99.	6-34-40-3W5	Ostracode zone - Basal Quartz	2127-2145 m	16.9 m
100.	14-23-41-4W5	Glauconitic Sandstone	2076.2-2094.2 m	18 m
101.	14-27-41-4W5	Glauconitic Sandstone	2104-2121.7 m	17.7 m
102.	11-17-43-5W5	Glauconitic Sandstone - Coal	2071-2111.6 m	18 m
103.	6-8-47-8W5	Ostracode zone	2099.5-21112.6 m	18 m
104.	6-1-51-12W5	Glauconitic Sandstone A, B	7190-7230 ft.	40 ft.
105.	8-2-53-12W5	Basal Quartz - Rock Creek Fm - Poker Chip Shale	2112-2148 m	35.9 m
106.	6-6-54-13W5	Basal Quartz	271-2089 m	18 m
107.	5-6-55-14W5	Basal Quartz	2114-2131 m	17 m
Line 3				
108.	16-12-52-26W4	Basal Quartz	1261-1279 m	18.6 m
109.	3-4-27-6W4	Basal Quartz	895-913 m	18 m
110.	6-23-33-11W4	Upper Mannville subgroup - Glauconitic Sandstone	1035-1053 m	18 m
111.	7-3-39-15W4	Upper Mannville subgroup - Glauconitic Sandstone	1132-1141 m	9 m
112.	14-30-50-23W4	Basal Quartz	1375-1382 m	6.5 m
113.	16-12-52-26W4	Basal Quartz	1263.2-1281.8 m	18.6 m
114.	9-30-54-27W4	Ostracode zone - Basal Quartz	1204-1222 m	18 m

